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DEVELOPMENT AND TESTING OF AN INFLATABLE, RIGIDIZABLE SPACE STRUCTURE EXPERIMENT

THESIS

Sarah K. Helms, Second Lieutenant, USAF

AFIT/GA/ENY/06-M03

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AFIT/GA/ENY/06-M03

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Presented to the Faculty

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Degree of Master of Science in Astronautical Engineering

Sarah K. Helms, B.S.

Second Lieutenant, USAF

March 2006

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Sarah K. Helms, B.S.

Second Lieutenant, USAF

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Abstract

Many recent space technology concepts require large space structures such as solar arrays and large aperture antennas; however, tight constraints on payload mass and volume often preclude their launch. Employing inflatable, rigidizable structures can reduce mass and volume while providing sufficient packing flexibility and structural stiffness. AFIT has developed RIGEX to flight-test this type of structure.

RIGEX will test the deployment and structural characteristics of three thermoplastic composite Sub-Tg tubes. Once launched on the Space Shuttle in 2007, the spaceflight results will be compared to lab data to validate on-orbit reliability and ground test methods.

This paper documents three main RIGEX development items: the Space Shuttle integration process, random vibration testing of the oven assembly, and development and application of the RIGEX structural model. The RIGEX launch integration process has been laid out and the first milestones, the RIGEX Preliminary Design Review and Phase 0/I Safety Review, were successfully completed in September 2005. Subsequently, random vibration testing of the prototype RIGEX oven assembly validated its structural integrity. Furthermore, a RIGEX structural model was developed using the finite element approach and NX Nastran for FEMAP software. The RIGEX FEM produced a first natural frequency of 242 Hz, meeting the NASA requirement with a margin of over 140 Hz. Overall, the RIGEX structural design has rapidly matured, meeting all NASA requirements thus far.

To My Family

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Thanks for the love and support of my husband, whose understanding and encouragement helped me maintain composure and a positive work ethic throughout the whole thesis process. Also, thanks to my parents who put the whole idea of greater education into my head in the first place long, long ago. A final thanks to Ed Tomme for his valuable insight and time spent proof-reading my thesis draft. The effort and support from all of my family and friends was very much appreciated.

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List of Abbreviations

Abbreviation	
AFIT	Air Force Institute of Technology
AFRL/VS	Air Force Research Laboratory Space Vehicle Directorate
ANDE	Atmospheric Neutral Density Experiment
ASD	acceleration spectral density
CAPE	Canister for all Payload Ejections
CDR	Critical Design Review
C&DH	command and data handling
CHUG	CAPE Hardware Users Guide
CONOPS	concept of operations
dB	decibel
DoD	Department of Defense
DOF	degrees of freedom
DSX	Deployable Structures Experiment
EM	Engineering Model
ESA	European Space Agency
FCP	Fracture Control Plan
FEA	finite element analysis
FEM	finite element model
FEMAP	Finite Element Modeling and Post-Processing software
FFT	Fast Fourier Transform

FRF	frequency response function
FRR	Flight Readiness Review
g	acceleration due to gravity
GAS	Get-Away-Special
grms	root mean square of gravitational acceleration
Hex	hexahedron element
Hz	hertz
IAE	Inflatable Antenna Experiment
ICD	Interface Control Document
ICU	Internal Cargo Unit
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Lyndon B. Johnson Space Center
lbf	pounds force
lbm	pounds mass
MEFL	maximum expected flight level
MOA	Memorandum of Agreement
MSVP	Mechanical Systems Verification Plan
mV/g	millivolt per unit of gravitational acceleration (g)
NASA	National Aeronautics and Space Administration
NET	no earlier than
NSTS	National Space Transportation System (aka. STS)
oct	octave

PDR	Preliminary Design Review
PI	Principle Investigator
PSD	power spectral density
psi	pounds per square inch
Quad	quadrilateral element
RIGEX	Rigidizable Inflatable Get-Away-Special Experiment
rms	root mean square
SDP	Safety Data Package
SERB	Space Experiment Review Board
SMC	Space and Missile Systems Center
SMP	Shape Memory Polymers
SR	Safety Review
STD	Technical Standard Document
STP	Space Test Program
STS	Space Transportation System
SVP	Structural Verification Plan
T_g	glass transition temperature
Tet	tetrahedron element
TIM	Technical Interchange Meeting
TM	technical memorandum
Tri	triangle element
USAF	United States Air Force
UV	ultraviolet

VLBI	Very Large Baseline Interferometry
vrms	voltage root mean square

DEVELOPMENT AND TESTING OF AN INFLATABLE, RIGIDIZABLE SPACE STRUCTURE EXPERIMENT

I. Introduction

1.1 Motivation

Space exploration has always been an expensive endeavor with many defined restrictions and limitations. Space-based experiments are bounded by many requirements in order to become successful, including physical dimension, weight, and cost. Inflatable structures have the potential to achieve greater efficiency in all of these categories. Inflatable structure concepts have been developed and tested over the last several decades providing enough data to ascertain their potential for low cost, high mechanical packaging efficiency, deployment reliability and low weight (13). The term inflatable structure indicates that a condensed configuration will be launched into space and then deployed by pressurization to its full intended form. This pressure must remain within the structure in order to keep it in a rigid, structurally stiff state. As documented by the Jet Propulsion Laboratory (JPL) at the California Institute of Technology, small leaks caused by material imperfections or damage by micro-meteoroids are unavoidable (17). These leaks make sufficient back-up inflation gas a necessity for long term success. This addition can be very costly in terms of volume, weight, and expense due to added or enlarged pressure system components. For some long-term missions, the added amount of inflation gas may be unaffordable altogether. Therefore, with the growing maturity of inflatable space structure technology, space rigidization is of great interest (17). Rigidization of an inflatable structure is a process whereby, following deployment via inflation, the structure is physically rigidized to the point where it will maintain its intended shape without reliance on continued pressurization.

Due to their potential benefits, combined inflatable, rigidizable structures are very intriguing for a variety of space applications. These structures, most with relatively high strength and stiffness, can provide "enhancements in the performance characteristics of many space deployable systems such as large antennas, solar arrays, and sunshields" due to their volume and mass advantages over conventional constructions (4). Figure 1.1 depicts a typical deployment process illustrating how a compact initial configuration is inflated into a large aperture antenna, in this case portraying the Inflatable Antenna Experiment (IAE). Inflatable, rigidizables can also be applied to large aperture sensorcraft, deployable booms, solar sails, and countless other large ultra-lightweight technologies yet to come into fruition.

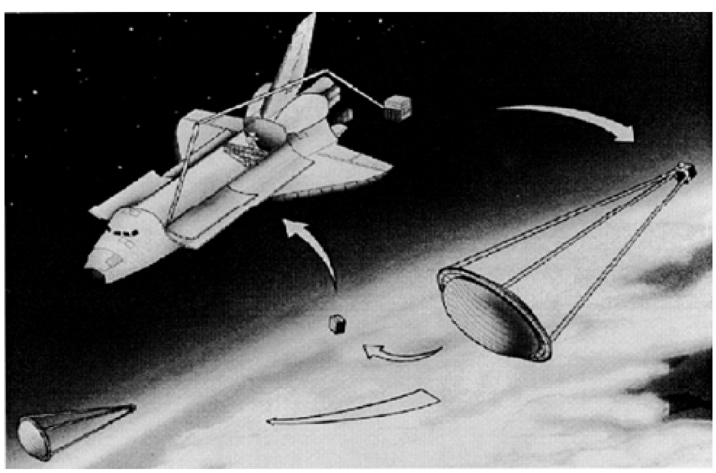


Figure 1.1 Inflatable Antenna Experiment Deployment (5)

While this innovative technology sounds very practical, the actual value of inflatable, rigidizable structures must be substantiated by research and successful on-orbit deployment. Multiple inflatable structure experiments have been proven in space. Also, an aluminum laminate inflatable, rigidizable material has been flown as a structural component in space on a few occasions (22). However, all other inflatable, rigidizable structure technologies have only been tested and deployed on the ground, in thermal vacuum chambers or on air tables. Spaceflight heritage of a proposed technology is considered a significant risk mitigation method, one that most inflatable, rigidizable structures do not have. For example, in the Teledesic satellite design, a commercial proposal by Boeing, "a mechanical system won due to the perceived development risk of inflatables" (8). In order to make this technology a marketable satellite application, steps to prove its functional capability and reliability must be made. According to R.E. Freeland in his article, *Inflatable Deployable Space Structures Technology Summary*, "the determination of how well the capability of this new class of space structures can meet the requirements of specific applications is based on a combination of issues that include structural concept maturity, technology database and the capability for analytical performance simulation" (13). Freeland names three main developmental issues that must be addressed for successful advancement of inflatable, rigidizable structures: concept maturity, technology database, and the capability for analytical performance simulation. An Air Force Institute of Technology (AFIT) project, named the Rigidizable Inflatable Get-Away-Special Experiment (RIGEX), was designed to address all three of these developmental issues.

1.2 RIGEX Overview

The Rigidizable Inflatable Get-Away-Special Experiment is a preliminary step in employing large-scale inflatable, rigidizable structures in space applications. RIGEX is a Space Shuttle payload bay container experiment that was originally designed in 2001 to mount inside of the National Aeronautics and Space Administration (NASA) Get-Away-Special (GAS) canister. NASA's plan to discontinue use of the GAS canister on future Space Shuttle flights led to modification of RIGEX in 2004. The experiment is now revised to mount inside the Canister for all Payload Ejections (CAPE) container as shown in Figures 1.2 and 1.3.

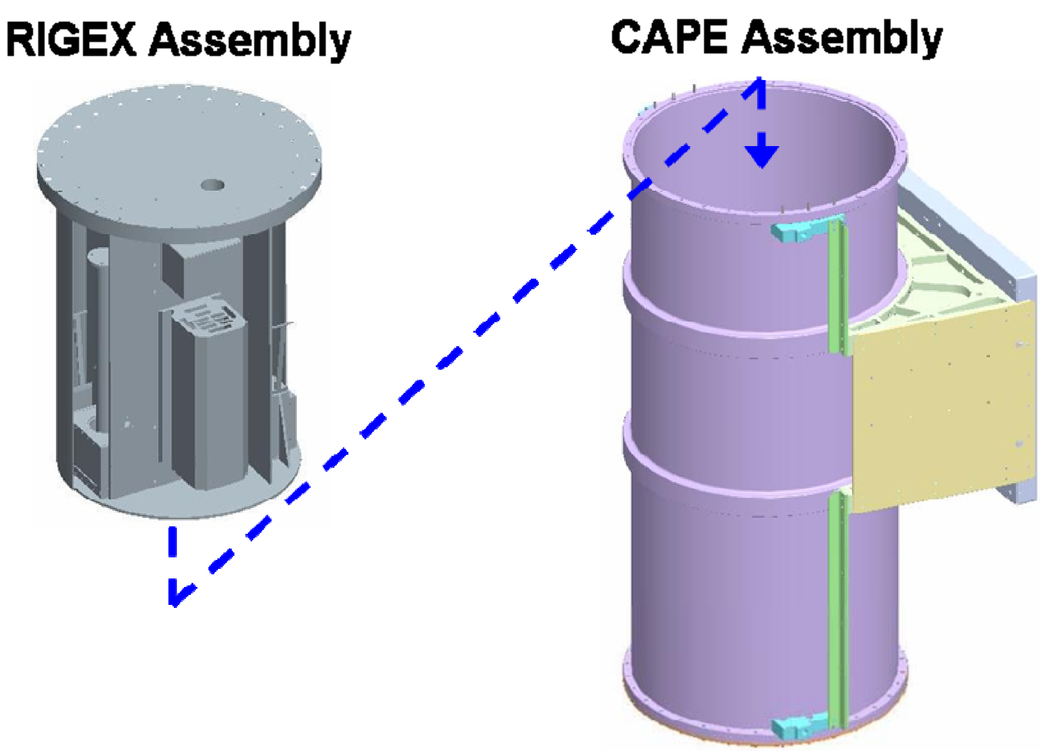


Figure 1.2 CAPE / RIGEX Configuration

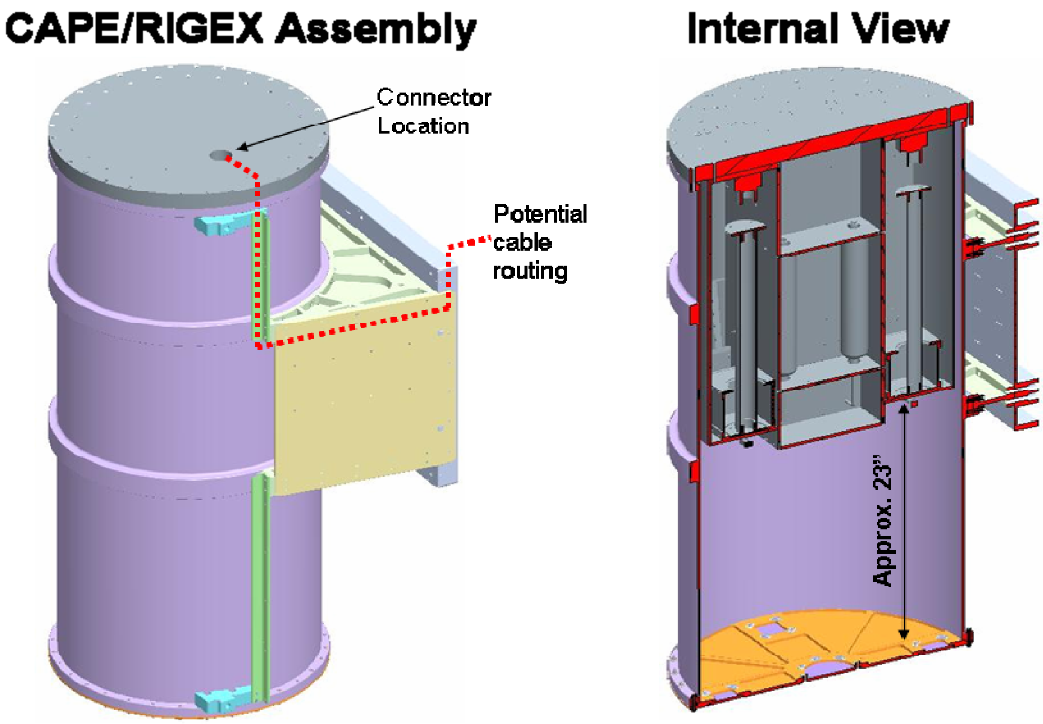


Figure 1.3   CAPE / RIGEX Assembly

CAPE was developed by Muniz Engineering, Inc. in conjunction with the DoD Space Test Program (STP) in response to the need for “a single ejection platform capable of ejecting payloads with requirements that are not compatible with current NASA developed ejection systems” (30). CAPE makes use of the previous GAS Beam mounting plate in order to attach the whole payload assembly onto the orbiter bay sidewall. The CAPE platform was an easily adaptable option for RIGEX due to the envelope and placement similarities, even though the CAPE ejection capability will not be exploited.

The goal of RIGEX is to take three 20 inch long inflatable, rigidizable tubes through their full deployment process and test their modal characteristics on orbit. The tubes were designed and manufactured by L'Garde, Inc. located in Tustin, California. Initially, multiple rigidization technologies were evaluated for use on RIGEX. These alternate methods will be discussed in Chapter II. A composite material characterized by a glass transition temperature (T_g) was chosen. Below the specified T_g the tubes are structurally stiff, but above the T_g tube material becomes malleable. Hence, this rigidization method is also known as Sub-Tg. The tubes used in RIGEX have a T_g of 125°C and are made up of a proprietary composite material consisting of Kevlar fibers with a polyurethane-based resin. A layer of Kapton tape has been wrapped around both the inside and outside of the composite tube construction. For structural characterization, two piezoelectric patches are mounted, opposing each other, at the base of each tube to serve as an input vibration source.

Each of the three tubes will be fixed to the RIGEX main structure at one end, while the opposing end will be left free to form a cantilevered configuration. The tubes have been folded into a stowed configuration by L'Garde using a z-fold design. Comparison of the stowed configuration to the deployed configuration is shown in Figure 1.4. The stowed configuration tube will be mounted to the RIGEX main structure inside a small heater box (or oven). This box will provide enough heat to transition the tube beyond its T_g providing flexibility for inflation.

There is a five step sequence of events for each Sub-Tg tube during the execution of RIGEX. First, a tube is heated to over 125°C within its oven. Then, the latch to the oven door is opened and the tube is pressurized with nitrogen gas causing inflation. After inflation, the tube remains pressurized until the temperature drops below the T_g and the tube becomes, once again, structurally stiff. This is the rigidization step. After rigidization is completed the nitrogen is vented out of the tube. Finally, the tube is excited by the two piezoelectric patches, and an accelerometer mounted at the cantilevered end collects modal characterization data.

Stowed Tube before Inflation

Deployed Tube after Inflation and Rigidization

Figure 1.4 Inflatable, Rigidizable Tubes: Stowed vs. Deployed Configuration

The whole deployment process is then repeated (heating, inflation, cooling, venting, and excitation) for the next tube, until all three tubes have been deployed. As each tube is deployed, the RIGEX subsystems will collect data on pressurization and temperature levels as well as a series of digital photographs for further documentation. RIGEX must then be returned to AFIT for analysis of the collected data because there will be no telemetry sent from the experiment while in orbit. All of the information gathered during experiment execution is stored internally on a PC-104 computer board. Current drawings of the full RIGEX detailed design are shown in Figure 1.5.

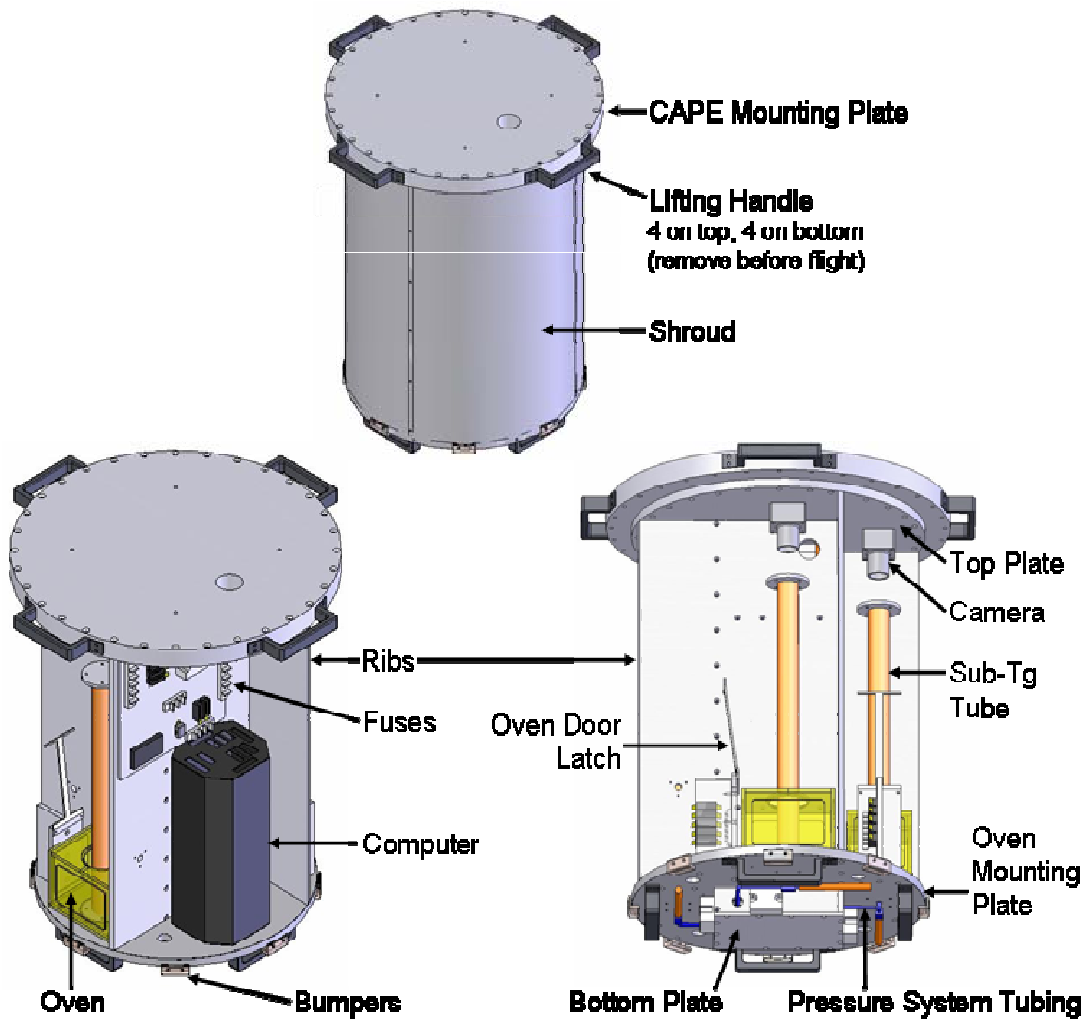


Figure 1.5 RIGEX Design Drawings – With and Without Shroud (14)

Once returned, the information gathered by RIGEX will be compared to similar modal characterization analysis done in the laboratory. Ground test data currently exists for a set of Sub-Tg tubes of the same make and configuration as those to be launched. Comparison of space versus ground test data will aid in determining the accuracy of laboratory simulation of structural performance. Together these analyses will provide a complete evaluation of the performance and reliability of L'Garde Sub-Tg tubes.

RIGEX was designed to increase knowledge and confidence in the use and performance of inflatable, rigidizable structures in space. RIGEX will add to structural concept maturity by recording deployment performance in space. The modal characterization data, both from space and in the lab, will add to the Sub-Tg tube technology database. Furthermore, the capability for analytical performance simulation will be assessed through comparison of the orbital data with the data gathered in the lab. Altogether, the launch, recovery and analysis of RIGEX will satisfy the three main development issues recognized by Freeland as necessary for advancement of inflatable, rigidizable technology in space.

1.3 Research Objectives

The top level RIGEX mission objective is as follows:

To verify and validate ground testing of inflation and rigidization methods for inflatable space structures against a zero-gravity environment. (9)

The top level research objective of this thesis is to continue timely development of RIGEX by satisfying some of the many requirements for launch, delineated by NASA. This thesis objective has led to three main goals:

1) Understand and continue the Space Shuttle payload bay integration process requirements and documentation
2) Execute prototype random vibration testing of the RIGEX heater box assembly to simulate and assess dynamic effects of the Space Shuttle environment during flight
3) Develop the RIGEX structural model

The primary goals begin with complete understanding of the National Space Transportation System (NSTS), or Space Shuttle, payload bay integration process. The second and third goals deal with the NASA requirement to prove structural integrity of RIGEX. The second goal, random vibration testing, is an AFIT structural risk mitigation test. This is an internal requirement in anticipation of mandatory acceptance testing of the fully assembled RIGEX flight model. The third goal, development of the RIGEX structural model, is a NASA safety analysis requirement for launch.

1.4 Thesis Summary

This document details three main objectives: the requirements and documentation process for space launch, random vibration testing and analysis of the oven assembly, and development and application of the RIGEX structural model. Chapter II will expound upon the history of inflatable, rigidizable structures along with the history of RIGEX itself. Chapter III explains the Space Shuttle launch requirements and documentation process involving NASA, the Air Force STP and AFIT. Chapter III also includes a description of the major RIGEX program milestones accomplished over the last year. Chapter IV discusses the methodology, test setup, testing, results and analysis of the oven assembly random vibration testing. Chapter V addresses the development and application of the RIGEX structural model using FEMAP (Finite Element Modeling and Post-Processing) Version 9.0 software for Finite Element Analysis. Conclusions drawn and recommendations based on these studies are discussed in Chapter IV.

II. Literature Review

"Concepts for inflatable deployable space structures have been under development and evaluation for almost 50 years" (13). This chapter will provide a historical overview of this period, beginning with the inflatable Echo Balloon series. It will then present a variety of acknowledged rigidization methods. Finally, this chapter will review the history of the Rigidizable Inflatable Get-Away-Special Experiment from its inception in 2001 through present day.

2.1 Historical Perspective

The cold war between the United States and the former Soviet Union spurred the first use of man-made satellites. Sputnik, the first artificial satellite, was launched in 1958. Due to limited launch vehicle technology, the most stringent constraints placed upon these early attempts at space exploration were on payload mass and volume. ECHO I, the first large space structure, was launched by NASA in 1960 to provide a space-based platform for passive communication. ECHO I reflected radio waves back to Earth using a 30.5 meter inflatable sphere made of an aluminized Mylar membrane, see Figure 2.1. This satellite is considered to be the first gossamer structure. Gossamer structures include all large space systems that are characterized by low mass and light loading circumstances (1). The ECHO Balloon series was the first to demonstrate the potential of inflatable structures. This program continued through the launch and utilization of

ECHO II in the early 1960's. ECHO II mimicked the ECHO I concept, obtaining orbit to permit passive communication; however, this model included the first flight-tested inflatable, rigidizable material: an aluminum laminate. This material performed well in space, and ECHO II remained functional in orbit for several years. "Since the launch of ECHO, many ideas for large systems in space have been vigorously pursued, however, relatively few have become operational" (1). The same aluminum laminate technology developed for ECHO II was later adopted in the Explorer IX and Explorer XIX atmospheric density experiments (42). These subsequent experiments also boasted successful outcomes.

Figure 2.1   Inflation Test of NASA's ECHO I Passive Communication Satellite (29)

Naturally, the other corporation to initiate technological advancement of inflatable structures was Goodyear. Beginning in the late 1950's and continuing into the early

1960's, Goodyear developed inflatable structure solutions for multiple concepts including the inflatable search radar antenna, radar calibration sphere, and lenticular inflatable parabolic reflector (13). Figure 2.2 shows the demonstration hardware of these three Goodyear concepts.

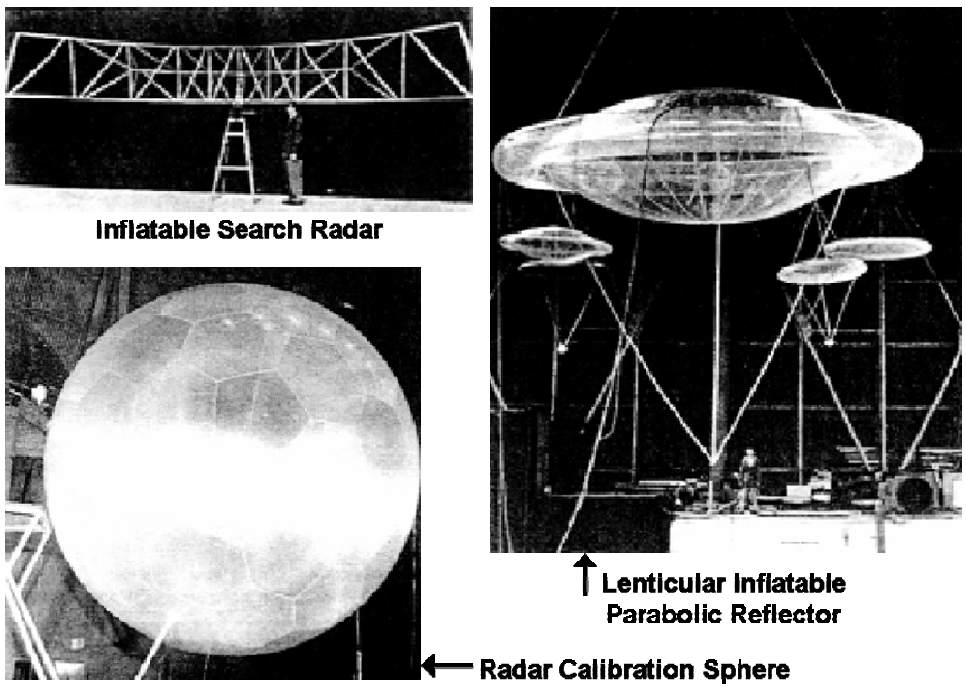


Figure 2.2 Selected Goodyear Inflatable Structure Concepts (13)

The inflatable search radar involved a rigidizable truss support structure with a parabolic curvature. The radar calibration sphere concept is very similar to the ECHO balloon series. This concept used hexagonal membrane panels, bonded together, to form a sphere when deployed. The lenticular inflatable parabolic reflector model includes a main reflector structure surrounded by a torus structure that acts as stiffening support to the reflector. A variety of different foams, flexible and rigid, were explored as possible rigidization methods for this concept (13). The Goodyear ground demonstration concepts added to the available pool of knowledge for inflatable structures.

In the late 1970's the European Space Agency (ESA) began their own exploration of inflatable space structures by sponsoring the development of two concepts at Contraves Space Division in Switzerland. The concepts were a reflector antenna and a sun shade structure. "The technology focus was for axisymmetric reflector antennas for Very Large Baseline Interferometry (VLBI), offset reflectors for mobile communications and sun shade support structures for telescopes and large sensors" (13). Around the same time, the US Air Force stepped up the use of inflatable structures as they began work on placing decoy and target structures in space. In the 1970's and mid 1980's, decoy satellites were not constructed with the expectation of a prolonged lifetime in orbit. The average system lifetime was rarely over a few hours, making rigidizable techniques unnecessary. Inflatable structures were used in this program because of their "inherent lower weight, lower packing volume, ruggedness (ability to withstand nuclear blasts), reliability, and ease in making curved surfaces" (42).

L'Garde, Inc. revisited exploration of rigidizable, inflatable structure technology for large space structure concepts in the late 1970's. Surprisingly, their findings suggested that a large inflatable antenna structure could maintain pressure on orbit for a large number of years without the use of a rigidization method. This change in thinking was driven by the fact that "meteoroid flux was now known to be much less than earlier estimates, and the large structures required very little pressure to maintain shape" (42). Thus, the IN-STEP Inflatable Antenna Experiment (IAE) was introduced without rigidization. This experiment was an on-orbit deployment demonstration of a lenticular reflector. The IAE objectives were to:

a) verify that large inflatable space structures can be built at low cost,
b) show that large inflatable space structures have high mechanical packaging efficiency,
c) demonstrate that this new class of space structure have high deployment reliability,
d) verify that large membrane reflectors can be manufactured with surface precision of a few millimeters rms, and
e) measure the reflector surface precision on orbit. (13)

"The IAE is an excellent example of a flight experiment to demonstrate the potential of lenticular gossamer structures" (1). The L'Garde, Inc. IAE was launched on the space shuttle in May 1996. Figure 2.3 shows the deployment process and ensuing configuration of the IAE.

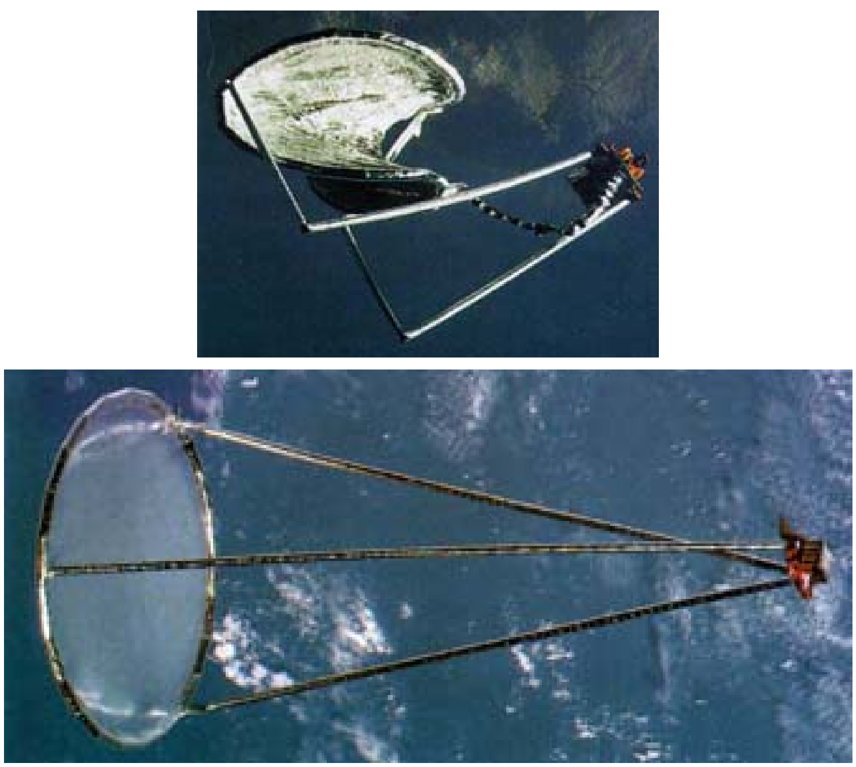


Figure 2.3   IN-STEP Inflatable Antenna Experiment (16)

The IAE proved deployment reliability, cost reduction, efficient packaging, and membrane surface precision. This successful, large inflatable antenna structure cost approximately $1,000,000, stowed a 14x28 meter structure in an office desk-sized container, and achieved surface precision within millimeters rms. While the IAE increased the known ability of inflatable structures to work properly without rigidization, it only proved practicality in space for very lightly loaded structures such as reflectors and concentrators. When lightly loaded, an inflatable structure can remain intact with approximately 10^{-6} psi of pressure, making it possible to provide ample backup gas. In order for an inflatable structure to carry any significant applied loads, a much greater pressurization level is required, indicating that a rigidizable structure is more appropriate. Each inflatable/rigidizable technology combination has a unique set of advantages and disadvantages tailoring it for specific applications. Therefore, L'Garde Inc. continues to explore rigidization techniques in addition to IAE inflatable structure technology (21).

Inflatable structures have cost, weight, and packaging volume benefits over mechanical systems. However, material imperfections, micro-meteoroids and orbital debris can create tears or leaks in structures over time limiting their application. Rigidization can alleviate these problems by providing a method to maintain composure of an inflatable structure without the need for sustained inflation pressure.

2.2 Rigidization Methods

As discussed earlier, rigidization techniques are being investigated due to the difficulty of providing enough backup pressurization to compensate for the small leaks that are inherent over time in inflatable structures. Rigidizables are defined as “materials that are initially flexible to facilitate inflation or deployment, and become rigid when exposed to an external influence” (4). There are a wide variety of rigidization techniques to date. Many different educational institutions, government agencies, and commercial industries have designed their own solutions to this problem. Both passive and active methods have been introduced, creating a wide range of physical properties and performance characteristics for space applications. One method of categorizing rigidization methods is by their material properties. Using this basis, the three main categories are (4):

1) Thermosetting Composite Materials
    - Rigidization mechanisms of thermoset materials include thermal curing, ultraviolet curing, foam stiffening, and inflation gas reaction.
2) Thermoplastic Composite Materials
    - Rigidization mechanisms of thermoplastic materials include second-order transition change, Shape Memory Polymers (SMP), chemically hibernated foams, and plasticizer or solvent boil-off systems.
3) Aluminum/Polymer Laminates
    - Rigidization of laminates is created by a compilation of thin-walled structures, made of aluminum/polymer membranes, laminated together to form a stiffened wall.

The main difference between thermoset and thermoplastic composites is that thermoplastics can be re-shaped multiple times, while thermoset composites are not reversible. An example from each category will be discussed in the following section.

2.2.1 Thermoset Composites

Thermoset composite materials use thermal curing, UV curing, foam stiffening, or an inflation gas reaction to apply rigidization (4). Thermally cured materials provide first-rate structural performance and design flexibility. They are typically composed of fibrous composite materials infused with thermoset polymer resins (4). Thermoset resins are chemically hardened with the application of heat. Many curing options are available. The most extensively tested methods include hardening by radiated solar illumination and heat applied internally by implanted resistive heaters. Depending on the method of applied heat, the hardening process ranges from one to several hours. As far back as the 1960's, the United States Air Force was leading research on thermal cured composites (4). The initial focus was on solar radiation cured materials, but application problems were encountered when it was realized that the material shelf-life was only a few days. Then in the 1990's, ILC Dover, Inc. ramped up research and development of a thermoset composite with built-in resistive heating elements. The epoxy chosen had a cure temperature of 120° C and, due to chemical adjustments made by the company, had a shelf-life of over two years. The stability and usefulness of this design was verified in multiple thermal vacuum tests. Preliminary assemblies of parabolic antenna structures and deployable booms were made with the ILC Dover, Inc. thermoset composite (4). In general, thermally cured composite rigidizables have high strength and stiffness properties. With the introduction of embedded heaters, the thermal cycle can be tightly controlled and predictable. Also, well-known and well-established manufacturing processes add to the applicability of this method.

Another method in this category is UV hardened composite materials, cured by 250-380 nanometer wavelength UV energy. This catalyst can be provided by the sun or an internal source within the structure. This category is rounded out by two other non-reversible rigidization processes: foam stiffening and inflation gas reaction.

Despite the numerous advantages of thermally cured composites, disadvantages also exist. As is true with all thermoset composites, the process is irreversible. This restricts the ground testing capability of all flight models. In addition, these structures usually require extensive insulation to prevent erroneous rigidization prior to deployment. Other disadvantages of this method include the power required for hardening and the potential for a very short material shelf-life.

2.2.2 Thermoplastic Composites

Thermoplastic composites take advantage of second-order transition change, shape memory behavior, chemically hibernated foams, or solvent boil-off characteristics to generate rigidization. SMPs are useful because they return to their original shape from a stowed position when heated above their glass transition temperature. SMPs are distinctive because they lend themselves well to the creation of unique shapes. Foams have been studied extensively as a variable, multipurpose technology. However, their usefulness in inflatable, rigidizable structures is limited, thus far, due to unsuccessful attainment of their predicted simplicity and stiffness benefits. Solvent boil-off composites make use of a plasticizer to makes the material soft. Rigidity is obtained when the plasticizer is exposed to the space environment and then allowed to evaporate. This technology is ingeniously simple. However, outgassing of the structure and the need for an environmental support system to prevent the plasticizer from evaporating preemptively are potential concerns (4).

While all of the above mentioned methods are currently being researched, the focus here will be on rigidization by second-order transition change. This distinctive class of materials displays excellent flexibility, has good structural performance, and is applicable to large complex concepts. An example of this type includes a resin infused fabric that rigidizes when cooled below its glass transition temperature (T_g), a tailorable entity. This method is commonly referred to as Sub-Tg because rigidization occurs below the T_g of the material. The Air Force Research Laboratory's Space Vehicle Directorate (AFRL/VS) is exploring this type of rigidization for use in large space structures (27). The concept they created is called the Deployable Structures Experiment (DSX). The study of large deployable structures is one of five different technical areas of investigation on DSX. DSX will utilize Sub-Tg inflatable, rigidizable material to construct a 25-meter boom and truss structure. A conceptual drawing of the experiment is shown in Figure 2.4. RIGEX and DSX have much in common because they will both test and develop the same Sub-Tg technology. However, unlike RIGEX, the DSX satellite will not be recovered. RIGEX is scheduled to fly and return prior to launch of DSX. Material property and fiber breakage data generated from the RIGEX project will be directly applicable to DSX. Therefore, the DSX Project Manger, Dr. Gregory Spanjers, has expressed interest in and will likely pay close attention to the outcome of

RIGEX (27). Therefore, RIGEX will act as a risk-mitigation effort for the AFRL/VS DSX satellite and other larger DoD missions in the future. The main advantages to this method of rigidization are its reversible and ground-testable nature, long shelf life, ability to create a nearly void-less composite, stable matrix, absence of maximum thickness limitation, and taliorable T_g (15). The disadvantages include a need for heater power and adverse reactions to *high* thermal environments, relative to the specific material T_g.

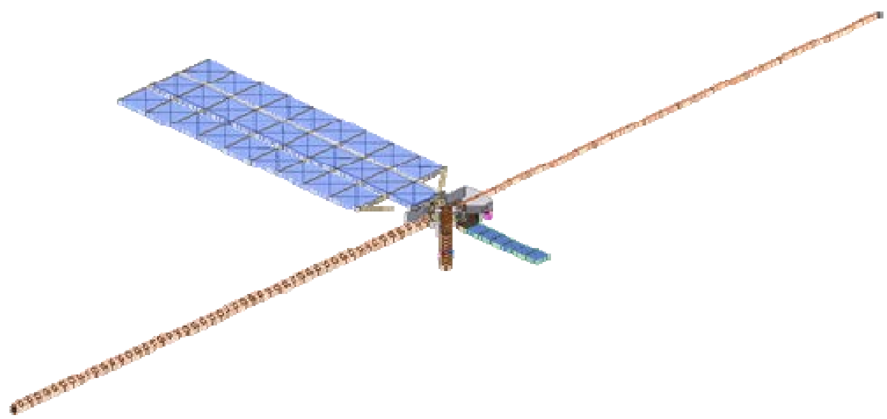


Figure 2.4   AFRL/VS Deployable Structures Experiment (27)

2.2.3   Aluminum Laminates

Many rigidization methods have been designed and lab tested. A variety of these techniques have been tested in thermal vacuum chambers or on air tables to simulate space conditions. However, only one rigidization method has been space proven. This method is a stressed aluminum laminate. “Aluminum laminate is the most mature space inflatable/rigidization technology; it has been flown on the early echo balloons in the 1960s and most recently on L’Garde’s Orbital Calibration Sphere in 2000, all with very successful results” (22).

The aluminum laminate method involves inflation, and then over-inflation, of a laminate structure past its yield point to remove packaging creases and create rigidization. For example, in L'Garde's Orbital Calibration Sphere a "laminate of '0' condition aluminum (normally 0.003 inches thick) 'sandwiched' between two layers of a thin plastic film (0.001 inch thick Kapton)" was used as a reflector for calibration of optical tracking systems (22). This 4.6 meter spherical structure can be seen in Figure 2.5. This method of rigidization has many benefits over the other methods. Aluminum laminates are not sensitive to thermal environments, hot or cold. Therefore, there is no constraint on the deployment environment and no need for thermal insulation. Also, they require no additional power, only pressurization, for inflation and rigidization. However, this method does not provide the strength required for load bearing structures in space. Therefore, aluminum laminates are not useful for large space structures or configurations with more than 100 pounds of compressive loading per element (22).

Figure 2.5 L'Garde's Optical Calibration Sphere (22)

All three rigidization categories, thermosetting composites, thermoplastic composites, and aluminum/polymer laminates, have distinct advantages and disadvantages. Although quite divergent in methodology, the technologies within all three categories produce a convergent end result: rigidization of an inflatable structure. RIGEX explores one such method, thermoplastic composite Sub-Tg tubes manufactured by L'Garde, Inc.

2.3 RIGEX History

Seven AFIT master's degree candidates have done previous work on the Rigidizable Inflatable Get-Away-Special Experiment. These individuals include John D. DiSebastian, Thomas G. Single, Thomas L. Philley Jr., David C. Moody, Raymond G. Holstein III, Steven N. Lindemuth, and Chad R. Moeller. Initial work on RIGEX began in 2001 with AFIT graduate student, John DiSebastian. DiSebastian utilized a systems engineering approach to make top-level RIGEX design decisions. He developed internal objectives, requirements, and constraints for the experiment and then used an iterative process to draw up a design to meet them. The RIGEX mission statement, developed by DiSebastian, reads:

To verify and validate ground testing of inflation and rigidization methods for inflatable space structures against a zero-gravity space environment. (9)

By the end of his research efforts, RIGEX was a self-contained, automated Get-Away-Special (GAS) canister experiment that contained three inflatable, rigidizable Sub-Tg tubes. Each tube was situated in its own experiment bay portion of the structure. This set-up left one bay location for the computer components and an inner bay for the power system, a large cluster of D-cell alkaline batteries. The RIGEX preliminary concept drawings can be seen in Figure 2.6.

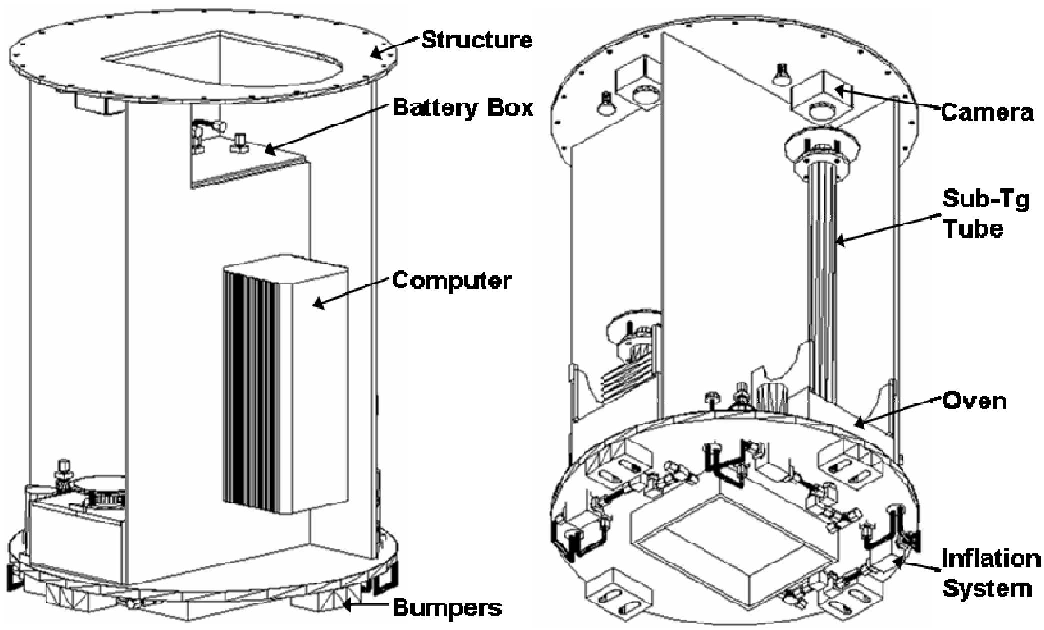


Figure 2.6 RIGEX Preliminary Design (9)

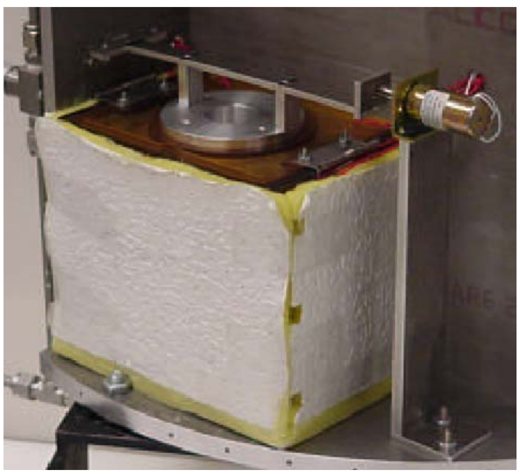
The second graduate student to work on RIGEX was Thomas Single in 2002. His work focused on experimental vibration testing of a set of deployed Sub-Tg tubes in a laboratory setting. A high-quality baseline for tube characterization on the ground is essential in order to draw performance and simulation conclusions once the flight data is retrieved. Single used a shaker to excite the tubes and a combination of accelerometers and a laser vibrometer to gather data for characterization of the modal properties. He also completed a series of tube tests in the AFIT vacuum chamber using piezoelectric patch transducers for excitation. Table 2.1 shows a summary of bending mode results for the short 20 inch tubes that were tested.

Table 2.1   Summary of Bending Mode Results, in Hertz, for 20” Deployed Tubes (38)

Mode #	Shaker (PZT driving)	Test Stand	Analytic	Vacuum Chamber	
				Ambient	Vacuum
1	33	32	1	51	51
2	63	63	60	64	64
3	231	231	196	228	232

Single’s data showed that, while the natural frequencies were somewhat dependant on test setup, the approximate values were consistent. He also showed that simplified Euler-Bernoulli beam theory provided a reasonable estimate to the frequency values found in the physical tests. Single’s thesis presents a wide variety of tube test data, including multiple test setups, acquisition systems, pressure settings, and thermal environments.

In 2003, Thomas Philley completed the first end-to-end deployment trials of the Sub-Tg folded tubes. A single tube was assembled on a partial mock-up of the RIGEX structure, known as the RIGEX quarter structure. The supporting subsystems, heater box, pressure components, and sensors, were assembled as well. The resultant configuration is shown in Figure 2.7, including before and after deployment photos. Philley also continued work on the vibration analysis of the deployed Sub-Tg tubes. He began with the conclusions and recommendations presented by Single and continued to construct a dense database of ground characterization information. The summary of his findings, including natural frequency and calculated damping ratio values, is included in Table 2.2.



Stowed Heater Box and Latch Assembly **Final Deployed State**

Figure 2.7 End-to-End Test: Stowed and Deployed Configurations (34)

Table 2.2 Sub-Tg Tube Natural Frequency and Damping Ratio Results (34)

First Bending Mode				
Parameter	**Table**	**Stand**	**Structure**	**Vacuum Tank**
Natural Frequency (Hz)	59.6875	37.5	60.3125	60.625
Damping Ratio (%)	0.78	0.83	0.52	1.04
Second Bending Mode				
Parameter	**Table**	**Stand**	**Structure**	**Vacuum Tank**
Natural Frequency (Hz)	660	542.1875	654.0625	651.25
Damping Ratio (%)	0.64	0.32	0.53	0.57

Raymond Holstein, Steven Lindemuth, and David Moody all completed master's theses involving RIGEX in 2004. Holstein's research involved structural analysis, Moody focused on the design and development of the RIGEX computer control system, and Lindemuth characterized the tube heating and inflation process. Holstein used the Finite Element Analysis (FEA) software, ABAQUS, to complete structural vibration analysis of the thermoplastic composite tubes, RIGEX quarter structure, and the full RIGEX structure. Examples of a few of these ABAQUS models are shown in Figure 2.8. Due to a discrepancy with the conclusions reported in Holstein's thesis, the results and analysis will not be included here. Instead, they will be revisited in Chapter V.

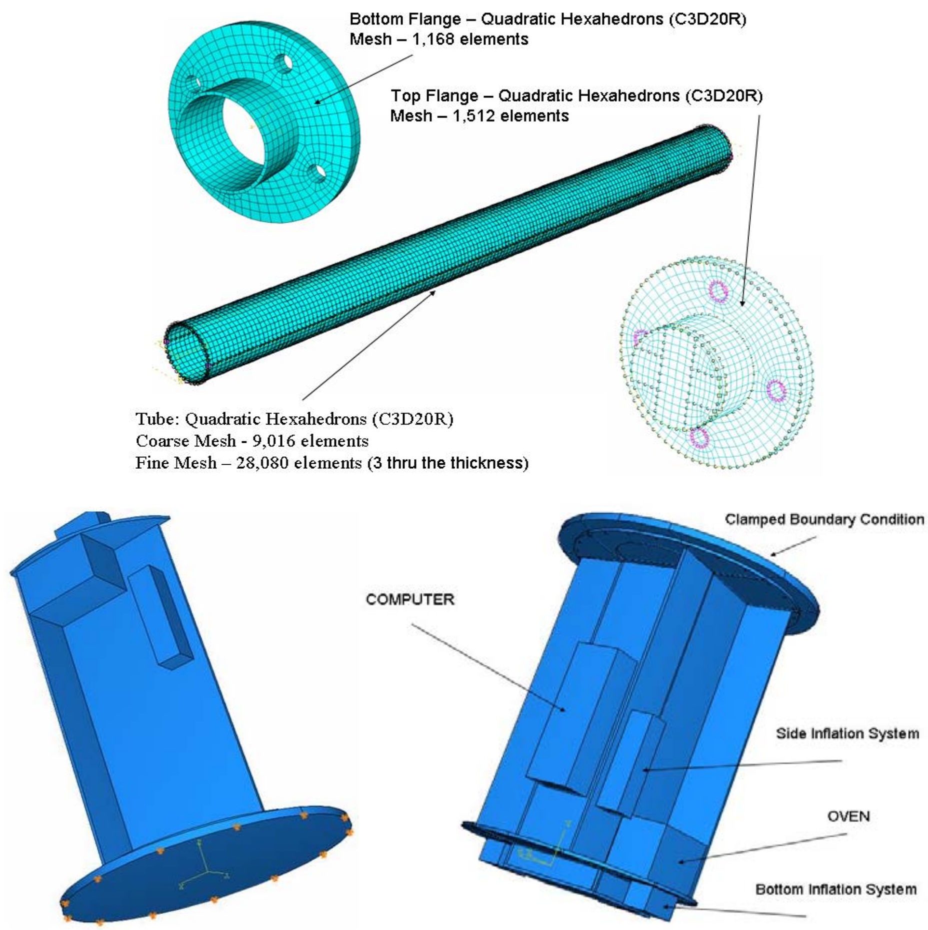


Figure 2.8 Compilation of ABAQUS Models Developed by Holstein (16)

Lindemuth completed a battery of tests to ensure that RIGEX was functionally operational and ready for spaceflight. The tests he performed are listed in Table 2.3 along with their specific objectives and success criteria. Lindemuth also handled many of the required design revisions that flowed from the completion of each test.

Table 2.3 Battery of Tests to Ensure Flight Readiness of RIGEX (23)

Test	Objective	Condition	Scale	Success Criteria
1. Heating	Determine heating profile	Ambient	¼	Reasonable and repeatable heating profile
2. Heating	Determine heating profile	Vacuum	¼	Reasonable and repeatable heating profile
3. Inflation	Test inflation system	Ambient	¼	Complete inflation
4. Inflation	Test C&DH	Ambient	¼	Execution of all programmed command actions
5. Inflation	Test C&DH	Vacuum	¼	Execution of all programmed command actions
6. Inflation	Test C&DH	Ambient	Full	Completion of all steps in RIGEX CONOPS
7. Inflation	Test C&DH	Vacuum	Full	Completion of all steps in RIGEX CONOPS

Moody engineered the RIGEX computer system to consist of two processors, “one for experiment control and sensor data collection and the second for image data collection” (28). These two processors were later designated the *data acquisitions computer* and *imaging computer* systems. Moody created the baseline design for the overall experiment control, temperature data collection, tube inflation and excitation actuation, imaging system acquisition, and program data files. He also developed the detailed RIGEX main event calendar, Figure 2.9, to document the overall operation of the computer control system.

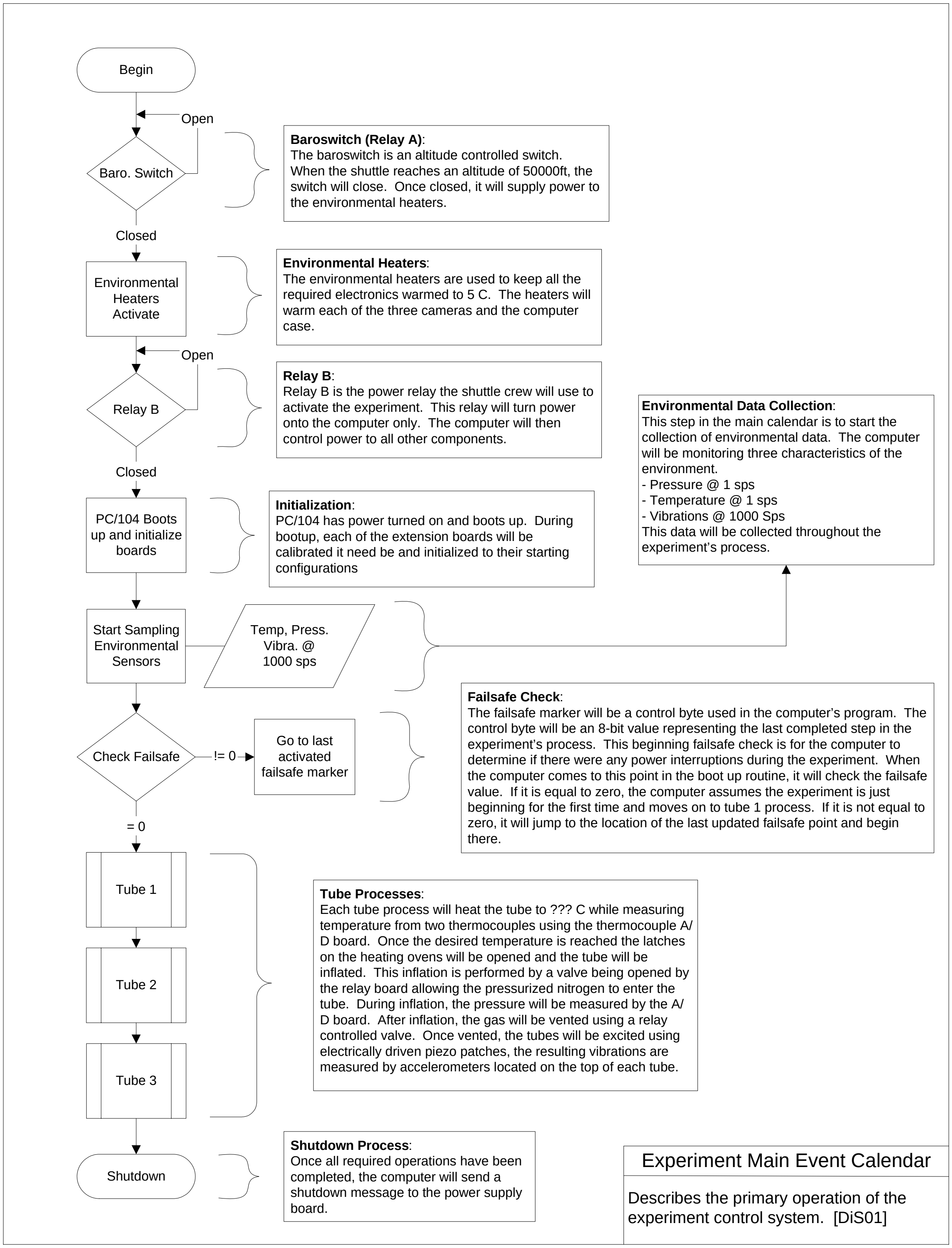


Figure 2.9 RIGEX Main Event Calendar (28)

Chad Moeller, the last of the group, completed his thesis in 2005 documenting the payload adaptation from the GAS canister to the CAPE. The physical differences between the GAS canister and CAPE are detailed in Table 2.4 and Figure 2.10.

Table 2.4 Comparison of Payload Envelopes (27)

First Bending Mode Parameter	**Table**	**Stand**	**Structure**	**Vacuum Tank**
Natural Frequency (Hz)	59.6875	37.5	60.3125	60.625
Damping Ratio (%)	0.78	0.83	0.52	1.04
Second Bending Mode Parameter	**Table**	**Stand**	**Structure**	**Vacuum Tank**
Natural Frequency (Hz)	660	542.1875	654.0625	651.25
Damping Ratio (%)	0.64	0.32	0.53	0.57

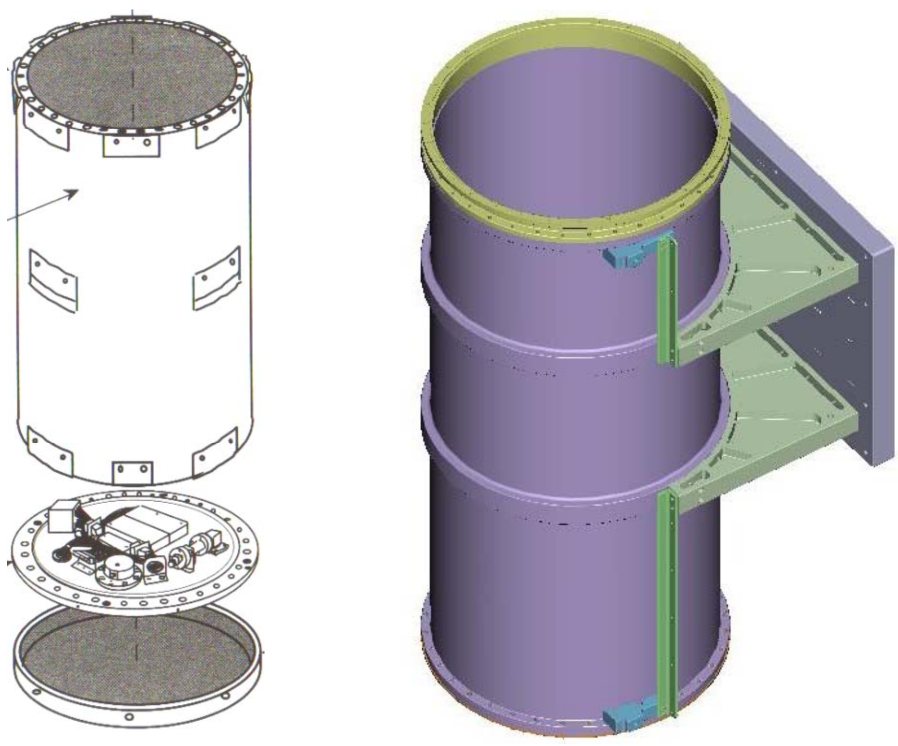


Figure 2.10 GAS Canister vs. CAPE (27)

The most influential change between these two containers was access to Space Shuttle power. RIGEX utilized an internal power subsystem when incorporated with the GAS canister; however, CAPE allows its payloads to obtain power through a direct Space Shuttle connection. This eliminated the need for the large alkaline batteries of the RIGEX power subsystem and freed up the interior bay to expand and improve the inflation subsystem. Table 2.5 lists the modification history of RIGEX addressed by Moeller. Furthermore, Moeller validated the Sub-Tg tube cooling profile for incorporation into the experiment control computer program and managed the manifestation of RIGEX onto the Space Shuttle. RIGEX was briefed at the Air Force and DoD Space Experiment Review Boards (SERBs) and was eventually manifested on the Space Shuttle through NASA and the Air Force Space Test Program (STP).

Table 2.5 RIGEX Modification History (27)

Subsystem	**Modification**	**Reason**
Main Structure	Computer access port removal	Stress concentration analysis
Main Structure	Component layout	Tube interference
Heater Box	Design changes	Inadequate performance tests
Heater Box	Dimensions altered	Poor fit to main structure
Pressure System	Component/layout alterations	Higher reliability and fit
Pressure System	Larger pressure vessels	Higher reliability and safety
Power	Battery pack to Shuttle power	Opportunistic, envelope change

In total, seven master's theses have been dedicated to the design, development, and testing of the RIGEX experiment from the years 2001 through 2004. A few of the main points in each thesis have been mentioned above. Two additional theses will be published in 2006, this document included, and two new master's students will continue work through 2008. Numerous undergraduate summer research students and academic instructors have put effort into this program over the years as well.

III. Launch Requirements and Documentation

RIGEX is a space experiment that exists for on-orbit data collection to advance the science of inflatable, rigidizable structures. However, RIGEX was designed without a telemetry system. All information gathered in space will be stored on an internal PC-104 computer board and must be returned to the Earth for analysis in order to be of any value. Therefore, RIGEX must fly such that it is retrievable after being in orbit. For this reason, RIGEX was designed to fly on NASA's Space Transportation System (STS).

The requirements and documentation process for launch on NASA's Space Shuttle is complex and involved, yet necessary. This process is vital because, except for research and development of the RIGEX science objectives, a large majority of the work involved for a successful launch concerns meeting NASA requirements for flight readiness. Spaceflight requirements are stringent for all launch vehicles to ensure the safety and success of an expensive, volatile launch vehicle and related facilities. Furthermore, an experiment hazard on the Space Shuttle could put the astronaut crew in danger, in addition to endangering the launch vehicle or ground facilities. Therefore, NASA requires that all Shuttle payloads abide by the instructions detailed in NSTS 1700.7B, *Safety Policy and Requirements for Payloads Using the Space Transportation System* (37). A wide variety of requirements documents, technical standard documents (STD), technical memorandums (TM), and safety guidelines stem from this root publication. This chapter delineates the RIGEX documentation process for launch on the STS, including discussion about all recently accomplished steps. The specific requirements expressed by NASA for structural verification of RIGEX are also discussed because they provided the core motivation for all studies and testing included in the remainder of this thesis.

3.1 NASA – STP – AFIT Coordination

Initial manifestation for launch of RIGEX was obtained through participation in the Air Force and Department of Defense Space Experiment Review Boards (SERBs). “The DoD Space Experiment Review Board community has agreed with the importance of RIGEX,” according to previous Master’s student Steven Lindemuth, because the “knowledge from a RIGEX mission will prove useful to both the government and commercial space industry” (23). RIGEX will launch within the NASA Space Shuttle payload bay, mounted inside of the USAF Space Test Program (STP) Canister for All Payload Ejections (CAPE). Therefore, RIGEX is subject to the NASA design and safety requirements as well as those included in the CAPE Hardware Users Guide (CHUG).

STP provides vital assistance to the RIGEX program as the payload manager and a launch integration resource center. STP is a part of Air Force Space and Missile Systems Center (SMC) under Air Force Space Command. STP is based at Kirtland Air Force Base in Albuquerque, New Mexico with a secondary operating location at Johnson Space Center (JSC) in Houston, Texas. STP is the “primary provider of mission design, spacecraft acquisition, integration, launch, and on-orbit operations for DoD’s most innovative space experiments, technologies and demonstrations” as well as the “single manager of all DoD payloads on the Space Shuttle and International Space Station” (10).

This office provides guidance on Shuttle manifestation and integration issues, valuable expertise gained from its long history of DoD/NASA collaboration. Since the first launch involving STP in 1967, over 170 missions have been executed involving more than 437 experiments using dedicated launch vehicles, secondaries, Shuttle/International Space Station (ISS) flights, or piggyback payload opportunities (10).

The typical mission life cycle contains three main phases: mission design, development, and execution (18). Figure 3.1 shows the overall process graphically.

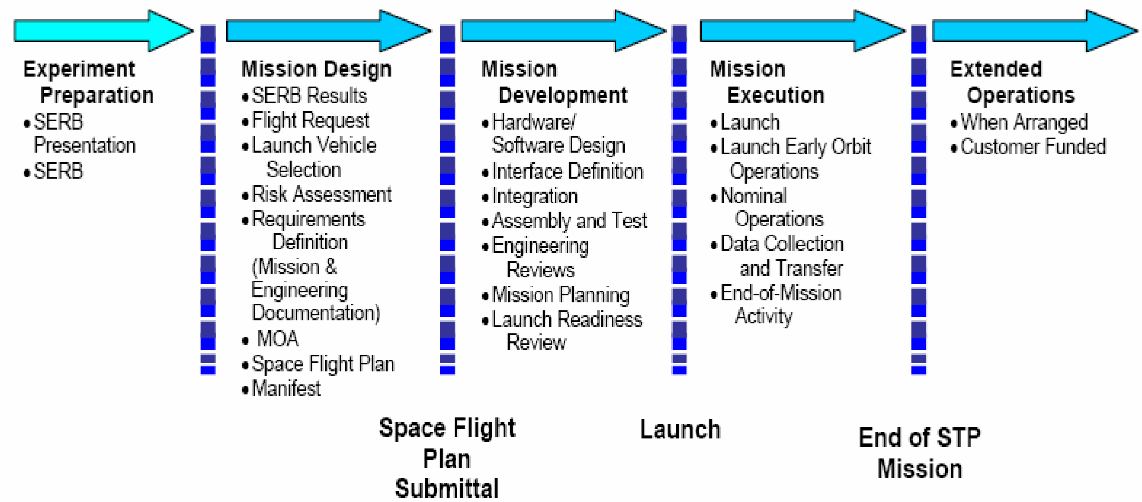


Figure 3.1 STP Mission Life Cycle Activities (18)

Over the 2001-2004 time span, RIGEX completed the experiment preparation phase by instigating experiment design and completing a developed concept brief at the Air Force and DoD SERBs. Presently, STP is in the process of wrapping up all unfinished business with the detailed mission design. Completion of this phase involves approval of submitted documentation at the NASA level. The STP Flight Request for launch on the

Shuttle was completed for RIGEX in 2004. In 2005, the Memorandum of Agreement (MOA) between SMC, STP, and AFIT was prepared and approved. Signing of this document means launch of RIGEX is manifested with STP. The manifestation process continues throughout mission development until the payload is assigned to and integrated on a specific STS mission. In late 2005, the STP Payload Requirements Document for RIGEX was prepared and approved by AFIT personnel as well (14).

The mission development phase began with a kickoff Technical Interchange Meeting (TIM) on July 21st, 2005. This was a meeting between the AFIT team and the STP personnel assigned to the RIGEX payload. The kickoff TIM is established for four main reasons: 1) review of the project management processes for Shuttle payload integration, 2) review of the Shuttle integration processes and requirements, 3) assessment of the RIGEX hardware definition and requirements, and 4) establishment of a plan to support the entirety of the RIGEX integration effort (19). After this meeting was held, weekly status telecons between STP and AFIT were put into place. Provided by STP at the Kickoff TIM, Figure 3.2 is an excellent visual representation of how all the elements of the integration process fit together in a sequential order. The payload development section consists mainly of Preliminary and Critical Design Reviews (PDR and CDR). The progression of this design review process, with respect to RIGEX, is discussed in Section 3.2 of this chapter. The payload safety process, including all documents and reviews, comprise the next grouping of elements in Figure 3.2. The RIGEX safety process evolution is presented in Section 3.3 of this chapter. All other required payload documentation is included in the shuttle integration section of Figure 3.2. The scope of this thesis is limited to payload documentation regarding structural verification and modeling of RIGEX. Therefore, Section 3.4 of this chapter outlines the NASA requirements for structural verification, as these supply the main motivation and guidance for the body of this thesis work.

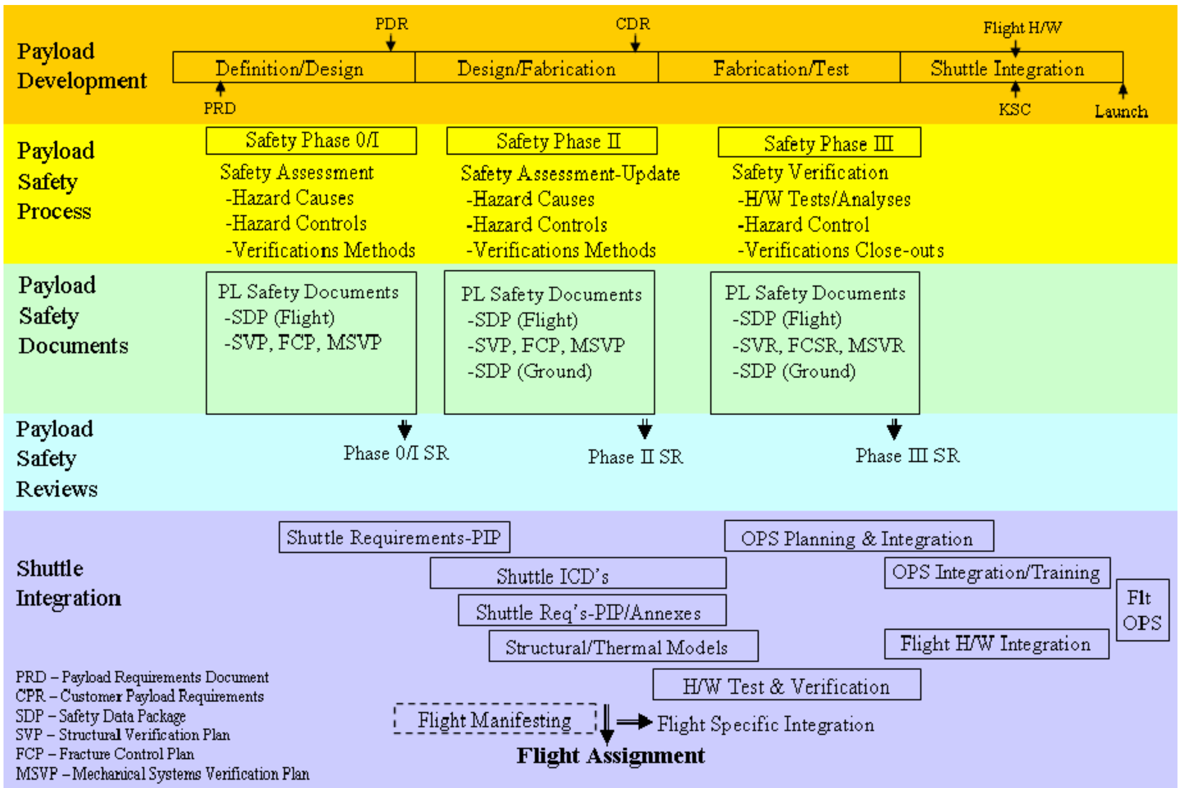


Figure 3.2 STS Payload Bay Integration Process (36)

3.2 Design Review Progression

The design review process consists of a PDR, CDR, and FRR (flight readiness review). The first major program milestone, the PDR, was successfully briefed by the RIGEX team to STP personnel on September 20th, 2005. The RIGEX team consists of the principle investigator (PI), Dr. Richard Cobb and all current graduate students involved with the experiment. This review exists in order to define and document the baseline RIGEX design and configuration. It also provides a venue for discussion of any payload issues and areas of risk with the STP team. Compliance with all requirements for launch vehicle interface, test plans and verification analyses are also reviewed. Appendix A includes the full PDR presentation for further indication of the RIGEX design detail included at this event. In general, the design reviews are completed so that compliance with all experiment requirements can be assessed in a formal manner before flight hardware is built. Figure 3.3 depicts the flow of experiment requirements as it should be accomplished according to the *Space Test Program (STP) Experimenters' Guide* (18).

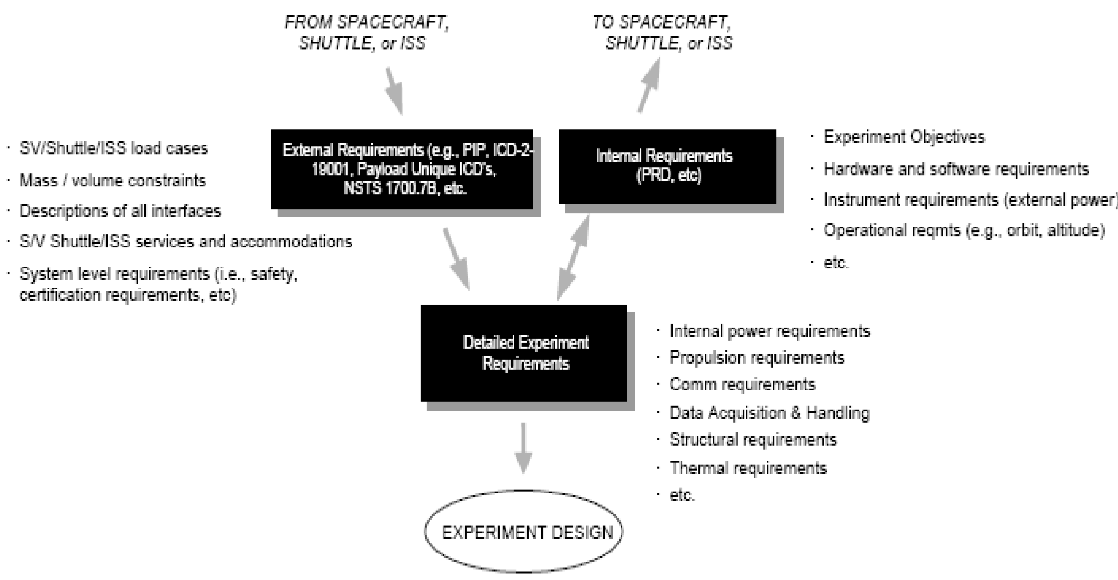


Figure 3.3 Internal and External Experiment Requirements (Shuttle / ISS) (18)

The RIGEX design will be revised until all requirements are satisfied. At this point, the experiment is ready for a Critical Design Review (CDR). At CDR the payload is expected to have all conceptual designs solidified and be requirement compliant. Substantial revisions required after CDR could negatively effect the payload launch date or may even cause cancellation of the launch manifest altogether. After a successful CDR, the payload should be ready to begin fabrication and assembly of the experiment flight model. RIGEX is expected to complete CDR in early April 2006.

3.3 Safety Review Process

NASA payload safety reviews (SRs) are held specifically for any experiment launched on the Shuttle. This process exists to ensure that all experiments comply with "Shuttle/ISS requirements through the systematic identification of hazards, the development of control methods, and the verification that the hazard controls have been successfully implemented" (18). Both ground and flight SRs must be accomplished and a supporting payload Safety Data Package (SDP) is required at each review. This package may include such documents as a Structural Verification Plan (SVP), Fracture Control Plan (FCP), Mechanical Systems Verification Plan (MSVP) and any experiment-specific hazard reports. The safety process is explicitly detailed in NASA document NSTS/ISS 13830, *Payload Safety Review and Data Submittal Requirements* (31). An overview of the SR timeline, with respect to months before launch, is shown in Figure 3.4.

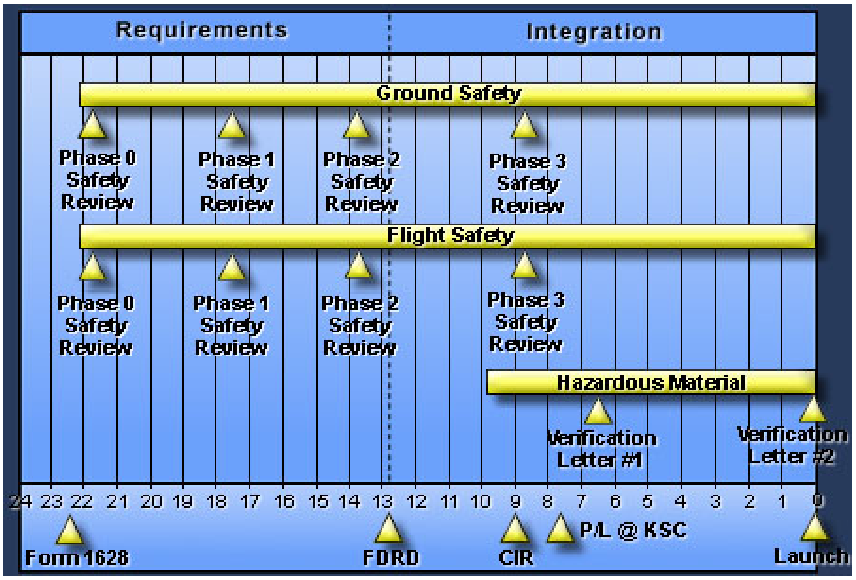


Figure 3.4 Normal Safety Review Timeline (19)

The RIGEX Phase 0/1 Flight Safety Review was held in Houston, Texas on December 14th, 2005. For this SR, the payload SDP consisted of various hazard reports, developed by the STP Safety Engineers with input from the AFIT team. The RIGEX inflation subsystem spurred a hazard report of particular interest at the safety review. This report was generated due to the fact that there is no known pressurization rating value for the Sub-Tg tubes. This concern was alleviated by adding a new calculation to the RIGEX containment analysis. Since the tubes could not be pressure rated, the safety concern was that overpressurization might cause a tube to burst, allowing a portion to detach and become free-floating inside the container. Through containment analysis it was shown that, even if the tube flange was separated from the rest of the structure by a pressure burst, the RIGEX shroud would be sufficient to keep the failure enclosed (14). Therefore, no damage would be done to CAPE, the Shuttle, or the astronauts due to free flying debris. Although structural failure of the Sub-Tg tubes would compromise the scientific objectives of the experiment, it is not considered a critical hazard. The details of the inflation subsystem and its most recent iterations are included in Appendix B for further reference. Overall, the initial RIGEX flight SR was a success and provided some very useful guidance for the remaining mission development.

3.4 RIGEX Structural Verification Requirements

The CAPE canister is scheduled to make its initial flight, carrying the Naval Research Laboratory developed Atmospheric Neutral Density Experiment (ANDE), in October 2006. RIGEX is the second scheduled flight of the CAPE hardware (3). While CAPE is a relatively new program, the container was designed as a reusable housing to carry small experiments into space. Therefore, a series of documents delineating its integration and testing procedures have already been developed. The *Canister for All Payload Ejections/Internal Cargo Unit (ICU) Structural Verification Plan* is one such document. This text, referred to as CAPE-SVP-0001, provides guidance for structural analysis and verification of any CAPE/ICU payload. This guidance is designed to ensure that all payload structures are verified as compatible with the Space Shuttle and that any CAPE payload can meet all mission objectives when subjected to anticipated load conditions (35). A summary of the structural verification approach, using analysis paired with physical testing, is included in Table 3.1. This table shows the minimum expected effort for structural validation. Specific load levels used for testing must be compliant with the design conditions stated in NSTS 21000-IDD-SML, the *Shuttle Orbiter/Small*

Payload Accommodation Interfaces document (2). CAPE-SVP-0001 contains all necessary information from NSTS 21000-IDD-SML compiled into a concise, CAPE-specific document. All of the qualification issues from Table 3.1 are addressed in this CAPE document.

Table 3.1 Summary of the CAPE / RIGEX Structural Verification Approach (35)

Qualification Issue	Analysis	Test
Structural Strength (static Limit, Ultimate)	X	
Structural Stiffness	X	
Random Vibration	X	X
Mechanical Shock	NA	NA
Mass properties	X	X
Thermal	X	X
Fracture	X	
Pressurization/Depressurization	X	

The studies included in this thesis are designed to address two qualification issues: random vibration and structural strength. The random vibration environment testing for RIGEX began with the prototype testing of the oven assembly that will be discussed in Chapter IV. The auto spectral density levels for testing will be introduced in Chapter IV along with their application in a laboratory setting. Per NASA-STD-5002, structural strength analysis will be assessed through a finite element model (FEM) (24). The development of the RIGEX FEM will be detailed in Chapter V. This model will analyze dynamic and static stress analysis to verify that the flight model material strength is adequate. A RIGEX FEM will eventually be incorporated into the CAPE FEM so that combined CAPE/RIGEX load analyses can be carried out. Altogether, these structural analyses were motivated by requirements for launch, delineated by NASA.

3.5 Program Milestones Overview

The RIGEX payload development has progressed significantly in the last two years. Completion of the SERB process propelled RIGEX into position as a manifested Space Shuttle experiment. Then, the kickoff TIM set the launch integration process into rapid motion. Table 3.2 lists the most up-to-date schedule for key RIGEX program milestones. This is a tentative schedule based upon progress of the RIGEX payload development, successful completion of safety reviews, and the fluidity of the Space Shuttle launch timetable. In addition, a flowchart of the integration process, with current RIGEX status highlighted, is included in Figure 3.5.

Table 3.2 Schedule of Key RIGEX Program Milestones

Assumption: Launch NET June 2007

RIGEX Kickoff	July-05
RIGEX PDR	September-05
RIGEX Phase 0/I Safety	December-05
RIGEX CDR	April-06
RIGEX Phase II Ground/GOWG	May-06
RIGEX Phase II Safety	May-06
RIGEX Phase III Safety	December-06
RIGEX Phase III Ground	January-07
RIGEX Delivery/Install	February-07
RIGEX Flight	NET June 07 (potentially STS-120)
RIGEX Launcher Removal	TBD

* schedule as of 29 January 2005

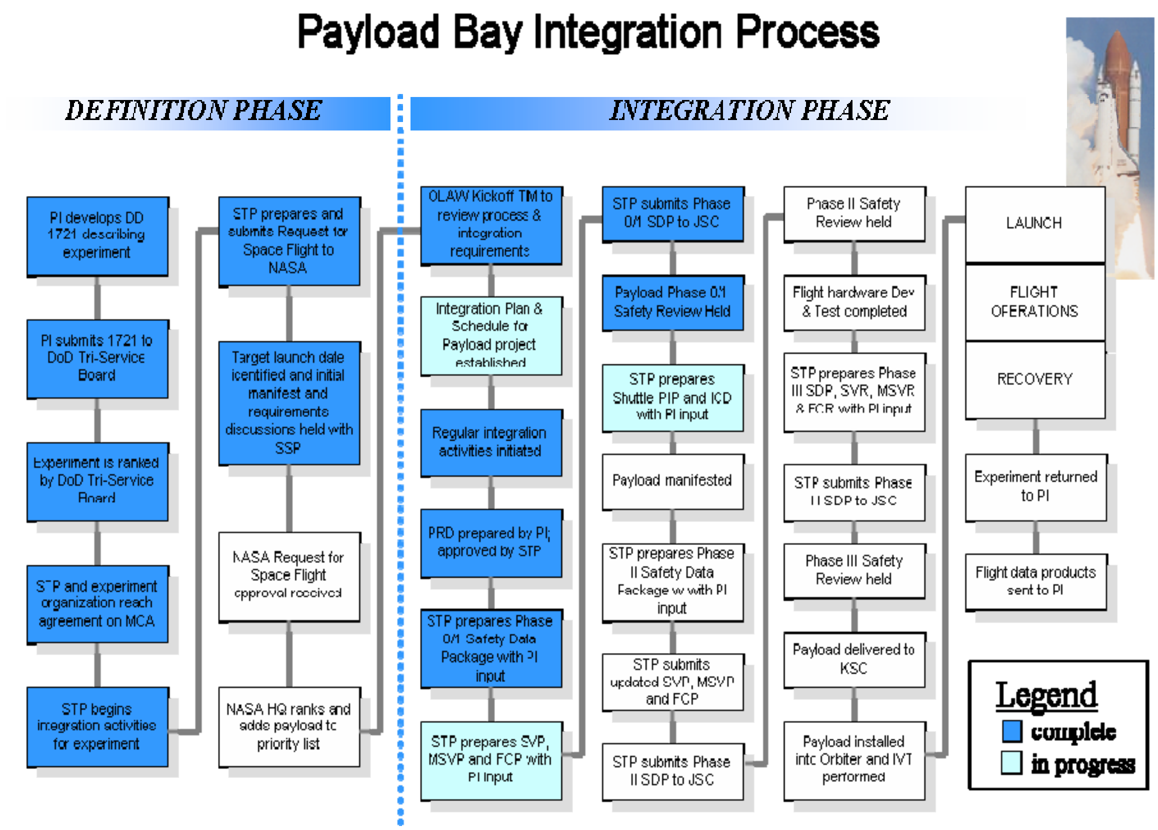


Figure 3.5 RIGEX Payload Integration Progress (36)

3.6 Summary

For obvious reasons, NASA upholds a strict requirements and documentation process for launch of any payload on its Space Shuttle. This chapter has presented the key points of this process: NASA-STP-AFIT coordination, experiment design review, payload safety review, and application of the requirements to structural verification specific research. Development of the RIGEX payload has advanced significantly in the past two years. The RIGEX conceptual design, or mission design phase, is nearing completion. The RIGEX mission development phase, including flight hardware development, is approximately one third complete. Remaining studies and documentation are motivated, not by scientific objectives of the mission, but by NASA constraints and requirements placed on RIGEX in order to be successfully integrated and launched on the Space Shuttle in 2007.

IV. Shuttle Environment Random Vibration Testing

The environments produced by Space Shuttle flight can be broken up into three main categories: 1) low frequency dynamic response to transient flight events, 2) high frequency random vibration transmitted throughout the launch vehicle via structural contact surfaces, and 3) the compound pressure environment created inside the launch vehicle by high frequency acoustic saturation (24). Each environment imposes a unique set of dynamic loads on payload components. Evaluation of structural integrity while under loading conditions representative of the three categories above is required for all NASA launched payloads (24). This chapter focuses on structural verification testing while under category two loading, excitation due to high frequency random vibration.

The random vibration levels during launch exceed those encountered during orbit, re-entry and landing; therefore, the launch profile is generally used as an all-inclusive analysis (2). In this case, the combined CAPE/RIGEX payload must show its ability to withstand the random vibration flight levels specified in the Structural Verification Plan (SVP) (6). Once the RIGEX flight model is assembled, acceptance level vibration testing must be done before integration onto the launch vehicle. “Acceptance tests are conducted to demonstrate satisfactory performance of flight systems relative to the expected environment and to reveal inadequacies in workmanship and material integrity” (33).

In anticipation of full scale testing, random vibration analysis of just the RIGEX oven assembly was accomplished. This analysis is referred to as component level qualification or prototype testing. Prototype testing was done in order to show design competency of dedicated test hardware (33). For RIGEX, prototype testing served as a structural confidence, risk mitigation method. This testing also provided an opportunity to develop familiarity with vibration testing methods, software, hardware, and test set-ups for future application.

The RIGEX random vibration analysis was accomplished through use of an electrodynamic vibration table available in the AFIT vibration laboratory. The following chapter includes random vibration testing methodology, test setup, results and analyses for this series of component level qualification testing. The conclusions and recommendations gathered from these results are presented in Chapter VI.

4.1 Methodology

The RIGEX oven assembly includes the oven, Sub-Tg tube, pin-puller, oven latch, oven mounting bracket, and the engineering model support structure. To test structural integrity of the RIGEX oven assembly it must be monitored while under a realistic flight loading environment. As noted, the vibrations felt by a payload during launch are one important portion of this environment. During launch it is generally assumed that the time domain phasing of each different frequency present is statistically uncorrelated. Therefore, this set of forces, dominated by non-deterministic parameters, is modeled as a random frequency event (24). The test profile used for random vibration is governed by an acceleration spectral density (ASD) function (12). This function defines acceleration amplitude versus frequency. From this profile function, the root mean square (rms) amplitude over the entire frequency range can be calculated. This value is also known as grms, which specifies acceleration due to gravity (g) as the units for amplitude, and is commonly used as an initial indication of overall profile intensity. Severe vibration is significant because it can affect joints in multi-component structures. A configuration may survive large static loads, but the compound stresses and strains created by a vibration environment, where amplitude will fluctuate with each triggered natural frequency, can be much more damaging. Accordingly, random vibration testing of a part can be a very informative tool in assessment of its structural integrity.

The MB Dynamics C40HP Electrodynamic Vibration Exciter "generates force by passing current through a wire that is placed in the presence of a magnetic field," a phenomenon known as Fleming's Left Hand Rule (25). Using this reaction to produce force, the excitation system drives sinusoidal displacement, velocity, and acceleration over a wide range of frequencies. Figure 4.1 illustrates how magnetic field and current interact to develop force in an electrodynamic vibration table (25). This figure includes an image of the AFIT vibration table with the generated force direction indicated.

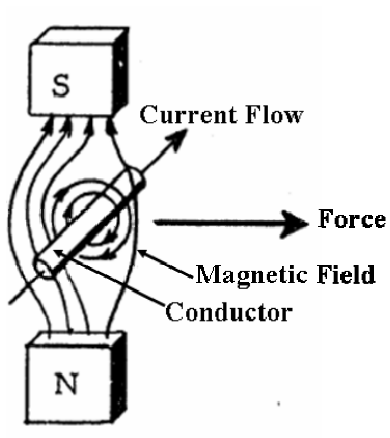


Figure 4.1 Fleming's Left Hand Rule Utilized in an Electrodynamic Vibe Table

The AFIT electrodynamic vibration table, hereafter referred to as a vibe table, utilizes a feedback control system to drive random vibration and sine sweep profiles. These profiles are determined by application of NASA compliance documents NSTS 21000-IDD-SML *Shuttle Orbiter/Small Payload Accommodation Interfaces* and NASA-STD-7001 *Payload Vibroacoustic Test Criteria* (2, 33). NSTS 21000-IDD-SML provides the X, Y, and Z axis random vibration environments for all hardware mounted on the Shuttle payload bay sidewall, such as CAPE/RIGEX. The X axis overall profile strength is 5.5 grms, Y axis is 7.7 grms, and Z axis is 7.0 grms (2). NASA-STD-7001 provides the minimum test levels for the workmanship profile. The purpose of this profile is to identify hardware defects and manufacturing flaws and its overall profile level is 6.8 grms (33). The maximum expected flight level (MEFL) must encompass all the NASA documented levels that apply to a payload. Therefore, the MEFL for CAPE/RIGEX, taken from the CAPE-SVP-0001 document, is a curve with an overall value of 8.2 grms. Figure 4.2 shows the CAPE/RIGEX MEFL profile along with the four NASA driven levels identified above. In accordance with NASA-STD-7001, RIGEX will be subjected to a MEFL, Gaussian amplitude random vibration distribution on each of its three orthogonal axes. Successful MEFL testing helps to assure that design performance and hardware workmanship will be adequate for spaceflight (33).

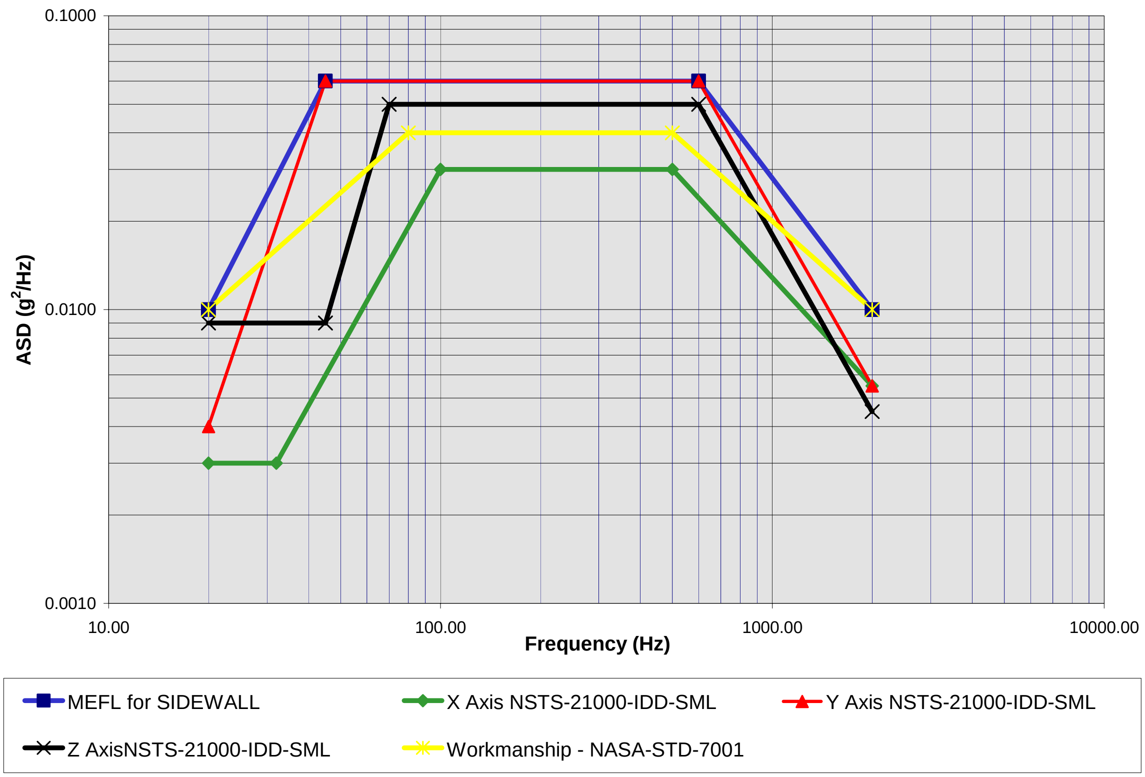


Figure 4.2 Shuttle Sidewall Random Vibration Design Conditions (35)

Generally accepted random vibration testing procedures are applied to the RIGEX prototype testing to uphold standard practice conformance. Testing a structure's ability to withstand random vibration begins with obtaining initial characterization of the structure. Therefore, a sine sweep test is used to acquire frequency response data over the full frequency range of the random vibration profile. Data gathered during the *initial* sine sweep produces a baseline power spectral density (PSD) for each acquisition accelerometer position. The PSD is a compilation of accelerometer output power over the tested frequency range. The power data (volts) can then be changed to acceleration data through use of calibration ratings (volts/g) predetermined in the hardware. Then, the

MEFL random vibration profile is used to induce spaceflight environment loading conditions. This test is run for two minutes, the length of time designated for prototype certification according to NASA-STD-7001 (33). In order to maintain active control of the vibe table excitation signal, the test will begin at a level 12 dB below the MEFL. Then in a series of ten second intervals, the ASD level will be increased until it reaches the full profile. This ensures that the testing profile is executed correctly and gives time for the computer to abort, before the maximum levels are reached, if problems with feedback control arise. If the system inadvertently exceeds the MEFL, and structural damage occurs, there is no way to determine whether the structure failed due to over-testing or poor design. Over-testing creates undue risk of test failure. Therefore, tolerances are set in the control software, in the form of alarm and abort limits, in order to prevent over-testing. After the random vibration profile is successfully completed, a *final* sine sweep test will be executed, identical to the *initial* sweep.

Structural health monitoring of the test article is accomplished by comparing the *initial* and *final* PSD data. This comparison can be made only when the test article is assumed to be a linear system. If the system is linear, the unique PSD generated by the structure will remain the same unless *damage* has occurred. *Damage* means any structural change, ranging from internal fatigue, loosened bolts, a shift in alignment of parts, chips, cracks, or complete structural failure. Therefore, PSD comparison is paired with visual inspection of the test article to verify that no critical damage has occurred. Figure 4.3 shows an example where comparison of two frequency response transfer functions indicates structural damage (20). Even though this example uses transfer functions to view data instead of PSDs, the frequency response is still being shown and it will produce similar attributes when damaged. In this example, a transfer function was obtained from a sample graphite/epoxy composite material. Then, a similar sample with induced delamination damage was tested. The graph in Figure 4.3 shows how delamination shifted the mid and high end transfer function peaks downward. When a structure's dynamic response shifts to a lower frequency it indicates a loss of stiffness in the structure (20). Loss of stiffness is an indication of structural damage. Other indications of damage in dynamic response analysis include added or missing peaks, and a single peak split into two side-by-side spikes. A transfer function is a ratio of output to input, therefore, the amplitude of its peaks reveals damage as well. On the other hand, when viewing PSDs the amplitude of the peaks cannot be used as a comparison factor. This is because the PSD does not include any input value data and is not a ratio, rather it is a straightforward spectral response. In PSDs the frequency value where peak responses occur is specific to the structure, but the amplitude of a peak is dependant on input excitation levels which may vary slightly from test to test.

Frequency Response Transfer Function of a Composite Material

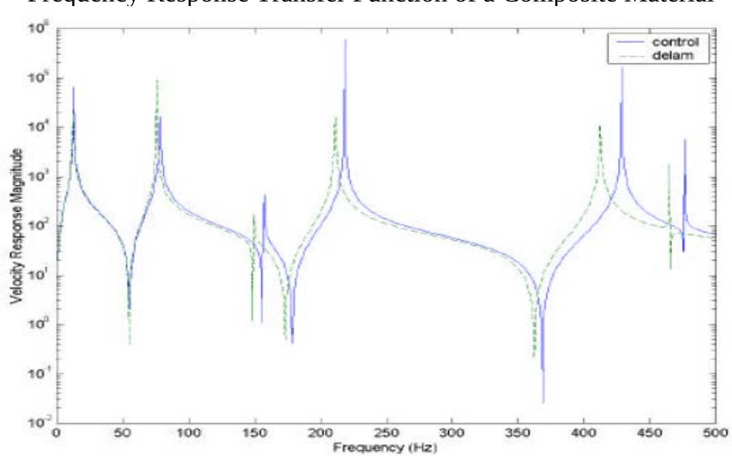


Figure 4.3   Example of Structural Health Monitoring via Frequency Response (20)

The sine sweep - random vibration - sine sweep process is a commonly accepted method of structural strength validation. This approach was used to test the CAPE/ANDE structure and, therefore, was adopted for testing of RIGEX as well (35). Three-axis prototype testing of the oven assembly at the MEFL will demonstrate structural integrity provided the PSDs indicate no critical damage has occurred. To further validate the test approach, multiple sine sweep tests will be run back-to-back with the full structure intact. The spectral response for each subsequent test should match to quantitatively verify that the structure has not changed. This test for method validation will be referred to in the results section as proof of repeatability. Also, if any bolts become loose during testing, tightening them back to their original position should fix the PSD damage. This repair should be observed in the data to further validate the test approach. In the future, all flight model bolts will be secured using two NASA approved locking mechanisms to prevent them from becoming loose during flight. This second test for method validation will be referred to as observation of repair in the results section. The random vibration testing, along with validation analyses, will provide structural verification of the RIGEX oven assembly with regard to random vibration launch loads.

4.2 Test Setup

The main equipment used for vibration testing was an electrodynamic vibration exciter (vibe table), cooling fan, signal amplifier, signal driving software, sliptable, RIGEX test article, control accelerometer, and a set of acquisition accelerometers. The MB Dynamics C40HP Electrodynamic Vibration Exciter served as the operating vibe table head. A Baldor 480 Volt industrial motor cooling fan and an MB Dynamics M Series Control Panel signal amplifier were positioned directly in line with the vibe table. The signal driving software was developed by MB Dynamics as well, and consisted of a Random Vibration Control System, Version 2.9.8r1 and a Sine Vibration Control System, Version 2.9.5r1. Two positions of the vibe head were used in order to test all three axes of the test article. Vertical positioning of the vibe head, perpendicular to the ground, allowed the RIGEX test article to be bolted directly on top of the vibe head surface. This induced excitation along the RIGEX Z axis. To complete X and Y axis testing, the vibe head was rotated to a horizontal position, parallel to the ground, and connected to an M/Rad Corporation Vibraglide sliptable. For this setup, the test article was bolted to the sliptable. The axis desired for testing was then clocked to align normal to the vibe head. The AFIT vibration laboratory set up, in the horizontal position, is shown in Figure 4.4.

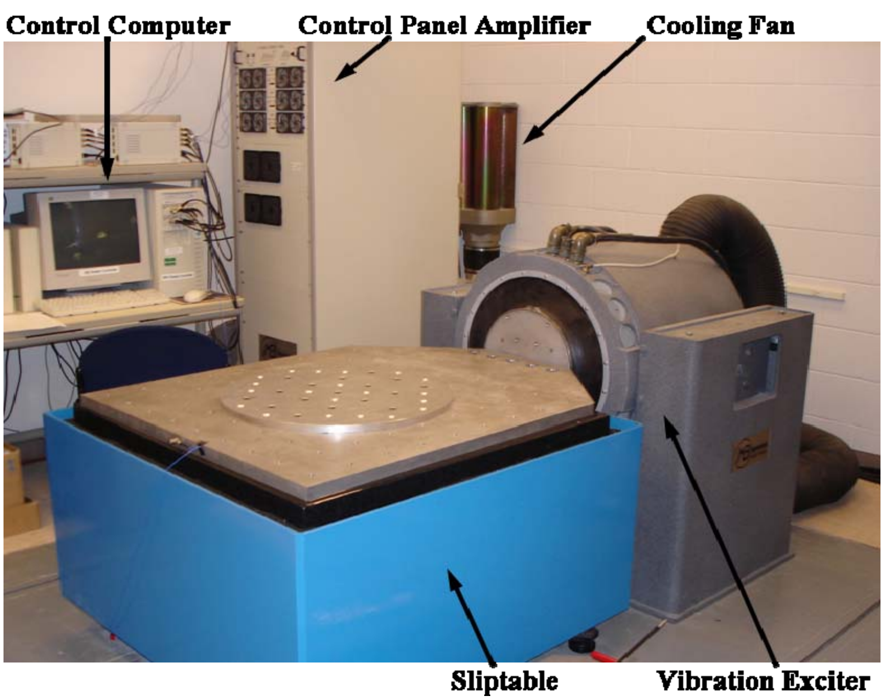


Figure 4.4   AFIT Electrodynamic Vibration Table Setup

For prototype testing of the oven assembly, the test article consisted of an oven assembly mounted onto the RIGEX engineering model structure. The engineering model (EM) structure, used for this test due to its availability and similarity to the flight model structure, is representative of the RIGEX design before it was modified for the CAPE canister. This structure has been previously used for subsystem fit testing and provides a close representation of how the oven assembly will be mounted in the flight model. The oven consists of a bottom and four sides bolted together, with two matching flaps that can hinge open or closed on the top. A photo of the prototype oven, with hinged flaps closed, is shown in Figure 4.5. In order to test the ability of this box to withstand launch vibration loads, the flaps must be secured like they will be during launch. This creates a domino effect of the parts necessary for the assembly. In all, four items are required to secure an oven into its launch position. The top flange of a Sub-Tg tube holds the oven flaps closed, an oven mounting bracket and latch are positioned to hold the Sub-Tg tube in place, and a pin-puller is installed to restrain the oven latch. The full oven assembly, mounted on the engineering model structure is shown in Figure 4.6.

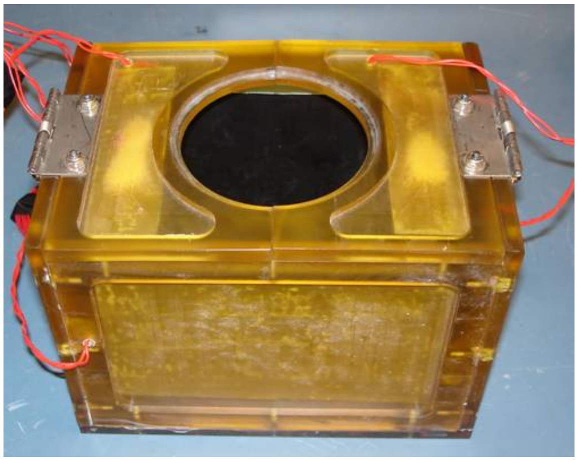


Figure 4.5 RIGEX Heater Box / Oven

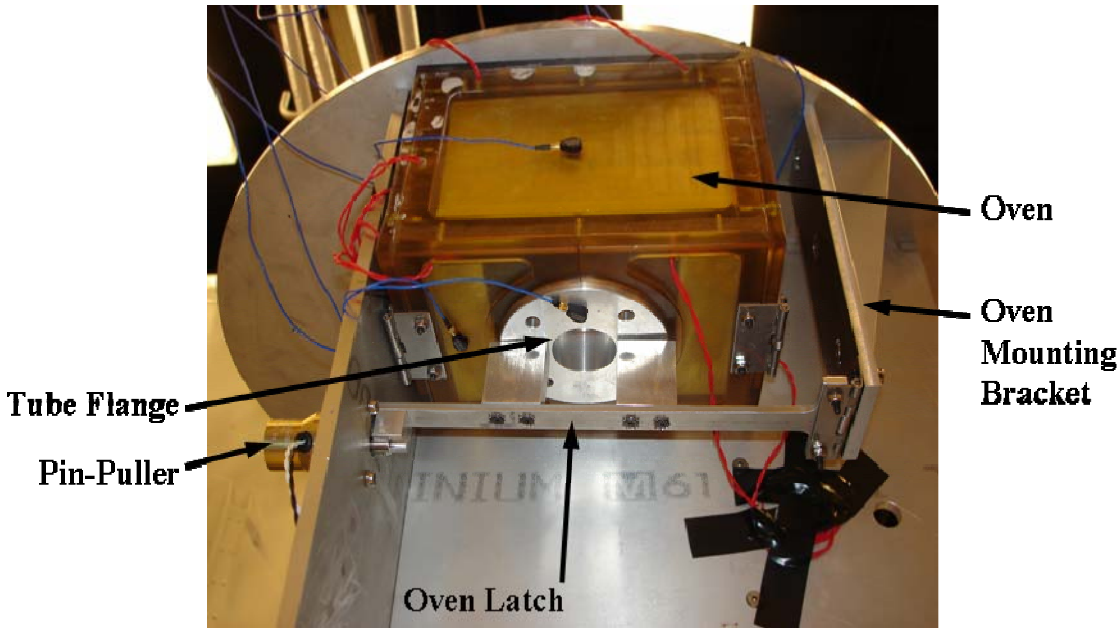
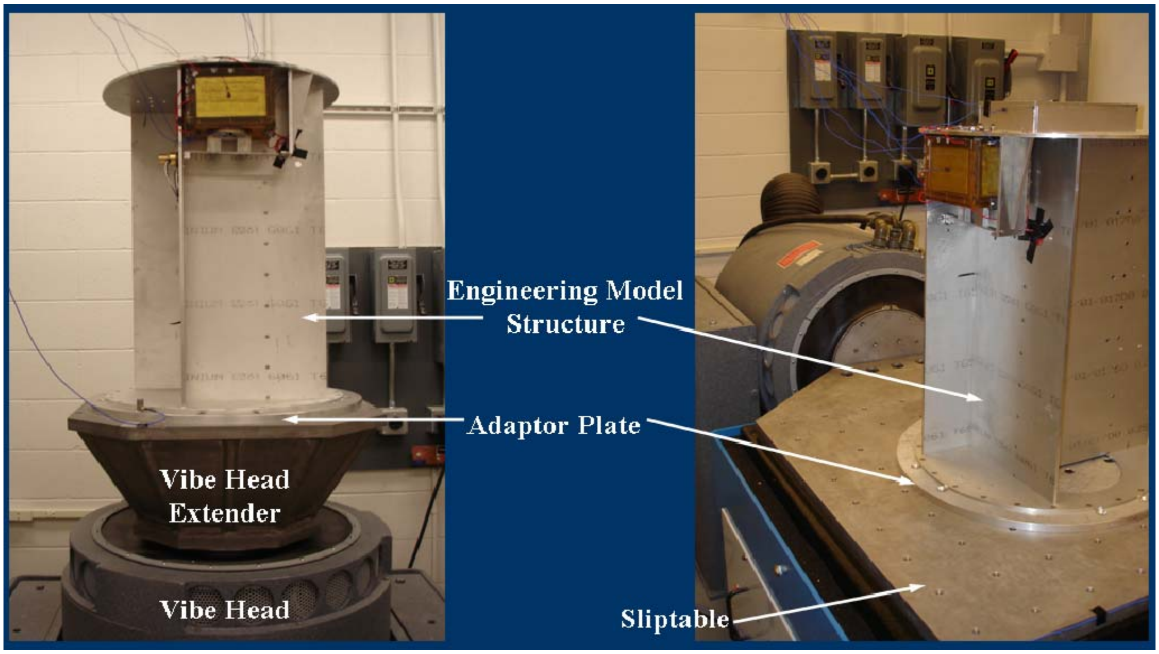


Figure 4.6   RIGEX Oven Assembly

With all necessary components for testing identified, the test article could be put together. First, the oven assembly was fully integrated onto the engineering model structure. Every bolt in the assembly used patchlock or locking washers as back-out protection during vibration. Then, the full test article was bolted onto the vibe table setup. The Z axis was tested first, with the vibe head positioned vertically. For this test setup a vibe head extender was used to increase the surface area of the vibe table. A bolt pattern adaptor plate was used to mount the RIGEX test article to the vibe head extender. Next, the vibe head was rotated to the horizontal position for X and Y axes testing. This setup incorporates use of a sliptable as the vibe table surface. The same bolt pattern adaptor plate employed in the Z axis testing was used to mount the RIGEX test article to the sliptable for this series of tests. Figure 4.7 shows the vertical and horizontal setups.



Vertical Setup (Z Axis Test) Horizontal Setup (X Axis Test)

Figure 4.7 Horizontal and Vertical Vibration Test Configurations

Eight accelerometers were used to gather data and control the profile during testing. A detailed description of accelerometer locations is included in Appendix C. The control accelerometer was gauged with an acceleration calibration standard to determine its rating. The calibration ratings for the seven acquisition accelerometers were taken directly from their corresponding data sheets. Table 4.1 lists these values.

Table 4.1 Accelerometer Calibration Ratings used for Vibration Testing

Accelerometer	Calibration Rating (mV/g)	Accelerometer	Calibration Rating (mV/g)
#1 Control	20.01(given) 20.2(calibrated)	#5 Tube Flange	9.96
#2 Oven Long Side	10.37	#6 Circular Plate	9.73
#3 Oven Short Side	10.07	#7 Square Plate	9.81
#4 Oven Top Flap	9.43	#8 Rib Plate	9.99

The MB Dynamics control software settings were pivotal for the successful execution of an accurate test run. Two different profiles, sine sweep and random vibration, were incorporated into the computer. First, a 0.25 g sine sweep profile ranging from 10 to 2000 Hz was commanded. This profile was set to run at the rate of two octaves per minute in accordance with NASA-STD-5002 (24). A ramp-up time of 15 seconds was used, making a full run of the sine sweep profile last a total of 4 minutes and 4 seconds. Alarm limits were set at ±3 dB from the 0.25 g profile and abort limits were set at ±6 dB. If the signal exceeded an alarm limit, a warning light was triggered. If the signal exceeded an abort limit the test stopped automatically. The same profile was used for both the *initial* and *final* sine sweeps.

Accurate execution of the random vibration profile was somewhat more complicated. The MEFL profile from Figure 4.2 was followed. The values used to create this profile are provided in Table 4.2 as follows:

Table 4.2 Maximum Expected Flight Level Profile Data (35)

FREQ(Hz)	ASD(g^2/Hz)	dB	OCT	dB/OCT	AREA	grms
20.00	0.0100	*	*	*	*	*
45.00	0.0600	7.78	1.17	6.65	0.78	0.88
600.00	0.0600	0.00	3.74	0.00	34.08	5.84
2000.00	0.0100	-7.78	1.74	-4.48	66.85	8.18

The same alarm and abort limits (±3 dB and ±6 dB respectively) used in the sine sweep profile were applied. The full strength MEFL was run for two minutes on each axis. The random vibration profiles were always started at excitation levels 12 dB below the profile. During Z axis testing, excitation occurred for ten seconds at -12 dB, -9 dB, -6 dB, and -3dB for a total ramp up time of 40 seconds. The full Z axis random vibration testing lasted 2 minutes and 40 seconds. However for X and Y axis testing, the feedback control system had trouble staying within limits when the four-level ramp up process was used. Therefore, the process was amended to only use -12 dB and -6 dB increments for the horizontal setup. This made the total time for X and Y axis random vibration testing 2 minutes 20 seconds. The random vibration control software included settings for a pretest, which ran at the start of test execution to gather initial transfer function data of the control accelerometer. Poor pretest data led to an inadequately controlled test, or failure of the test to begin at all. The pretest settings proved to be the most sensitive and most important. The pretest values used for testing are included in Table 4.3.

Table 4.3   Random Vibration Pretest Input Values

	Start VRMS	Max VRMS	DOF	Amplifier Gain
Z Axis	0.02	0.15	30	4
X / Y Axes	0.075	0.15	60	6

VRMS stands for voltage root mean square, DOF indicates the degrees of freedom used in creating the signal transfer function, and the amplifier gain was set via a dial on the M Series Control Panel. The pretest excitation signal started at a level indicated by the Start VRMS and doubled in power until an acceptable signal from the control accelerometer was received. If the excitation signal reached the Max VRMS level without receiving a clear signal from the control accelerometer above the noise floor, the test was aborted and a *pretest failed: bad signal* indication was produced. Once a satisfactory pretest transfer function was obtained, the random vibration profile proceeded as programmed until full MEFL was tested for a full two minutes.

One issue brought forth during test setup was the clocking of RIGEX on CAPE. The vibration testing profiles delineated in NASA documentation are specific to the Space Shuttle coordinate system. The CAPE-SVP-0001 document took the Shuttle profiles and tailored them to the CAPE coordinate system (35). The RIGEX coordinate system is similar to the CAPE defined coordinate system, shown in Figure 4.8.

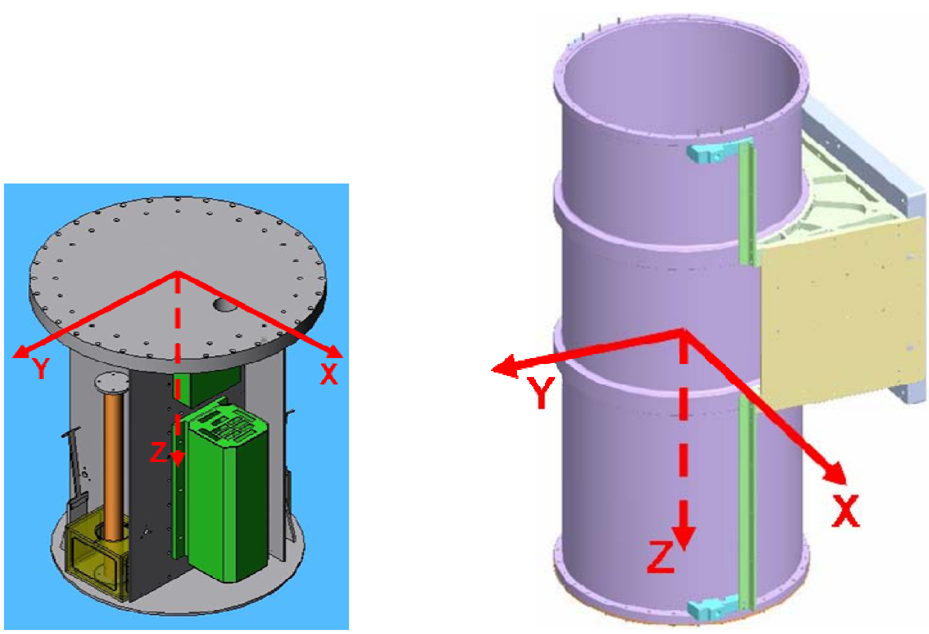


Figure 4.8   RIGEX and CAPE Coordinate Systems

The two structures share Z axes, except that the origin is offset to one end for RIGEX but centered in the length of the canister for CAPE. However, the specific clocking of the X and Y axes of RIGEX with respect to those on CAPE has not been determined. Discussion with STP clarified that RIGEX will be clocked specifically on CAPE when the CAPE-RIGEX Interface Control Document (ICD) is written. Furthermore, until the electrical interface is completed and payload mass and moment of inertia calculations are solidified, this ICD will not be finalized. Therefore, pending completion of the CAPE-RIGEX ICD, the RIGEX axes were assumed to be coincident with the CAPE coordinate system. The RIGEX coordinate system was used for application of the random vibration profiles for prototype testing. Once the CAPE-RIGEX clocking is determined, projection of the CAPE coordinate system onto RIGEX will be used for test application. If a difference between the two exists, it must be noted before any correlation between tests can be made.

Once the hardware and software setups were finished and functioning correctly, the structural verification test method was executed. The Z axis was tested first. After rotation of the vibe head to the horizontal position the X axis was tested, followed by the Y axis. The data plots generated from the sine sweep tests were evaluated after each random vibration in order to determine if damage occurred. Once satisfied that the test article was still structurally sound, the setup was changed until all axes were tested.

4.3 Results and Analysis

Shuttle environment vibration testing produced PSD data for each accelerometer location. An *initial* sine sweep provided baseline characterization of the structure. The *final* sine sweep represented characterization of the structure including any changes due to random vibration damage. After each *final* sweep, all bolts on the structure were checked and retightened. The last sine sweep, referred to as the *repaired* version, was completed after all accessible bolts were tightened. This *repaired* sweep made it possible to observe the change in PSDs due to loose bolts. Before analysis of the data is presented, tests validating the dynamic frequency response method for structural health monitoring will be reviewed. The two validation analyses used were proof of repeatability and observation of repair.

4.3.1 Proof of Repeatability

The baseline assumption of structural health monitoring on a linear system is that, with a specified sinusoidal sweep input, a healthy structure will always exhibit the same frequency response. Any difference between two test results indicates that the structure has changed or been damaged sometime between the last two tests. Due to unique material construction and high complexity of the heater box and Sub-Tg tube assembly, a high amount of vibration noise (from non-linearities) relative to the output signal was anticipated. This fact caused concern that the PSDs would not match up from one test run to the next, even if the tests were run consecutively with no damage to the structure in between. Therefore, the first sine sweep test was repeated to check correlation between the results. If the frequency response method for structural monitoring holds, the PSDs produced from accelerometers in the first sweep should overlap those produced in the second sweep. The Z axis setup was the first position tested. The accelerometers located on the oven door flap, Sub-Tg tube flange, oven mounting plate, and square plate were all aligned to measure Z axis accelerations. Data was obtained from all seven acquisition accelerometers; however, the ones aligned with the axis being excited produced the cleanest and highest amplitude responses. The other accelerometers only recorded the relatively small amount of vibration induced by acceleration propagated perpendicular to the driving input. Therefore, the four accelerometers mounted in the Z direction were of particular interest for this analysis. In the end, back-to-back sine sweeps did produce virtually identical frequency response results on all accelerometers present. Figure 4.9 shows PSD data obtained from the four accelerometers aligned with the Z axis. The two sweeps are almost indistinguishable, proving that the structure produces a signature PSD when excited by a common sine sweep.

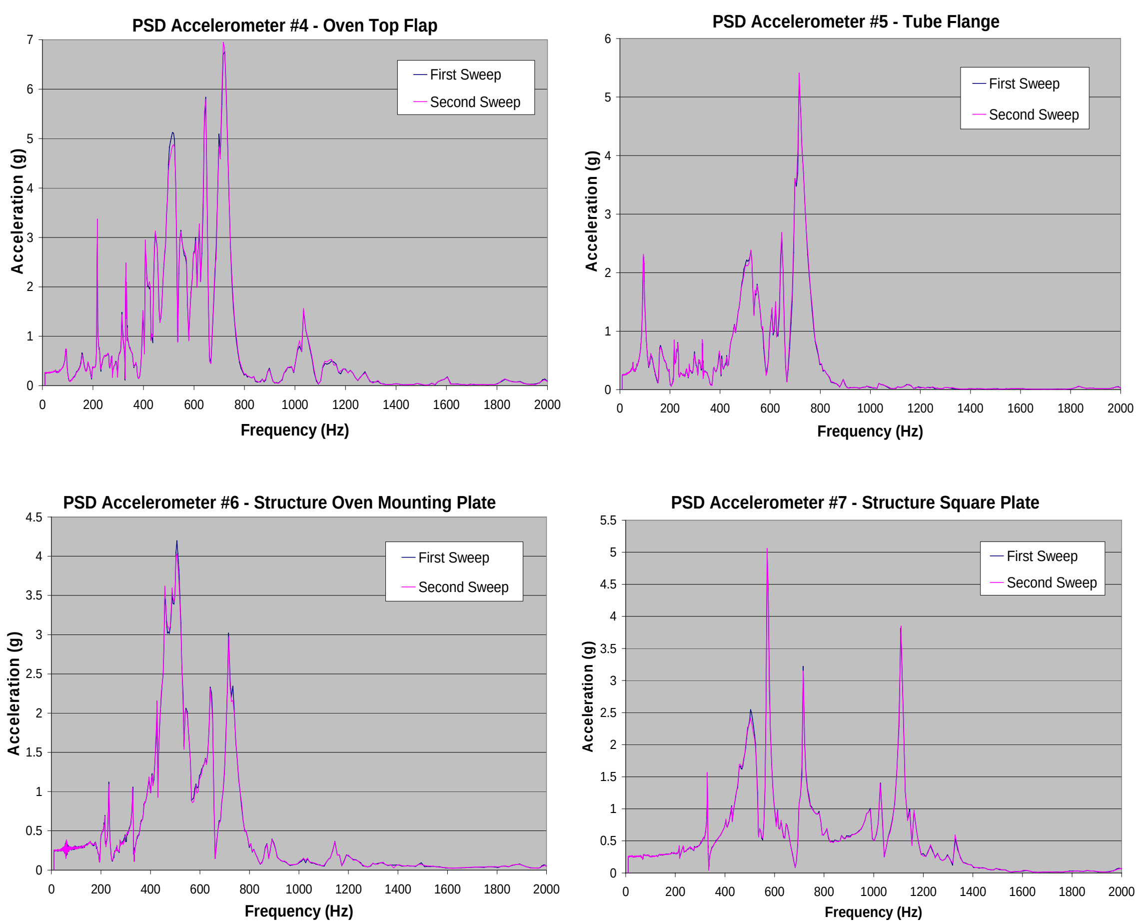


Figure 4.9 Proof of Repeatability Graphs for Accelerometers #4-7

4.3.2 Observation of Repair

Another validation of structural health monitoring via frequency response analysis involves graphical observation of repair. This was accomplished when the bolts were tightened after every *final* sine sweep test. A third *repaired* sine sweep was then accomplished to observe the shift in PSD peaks due to loose bolts. One bolt pattern was not tightened between tests because it was sandwiched between the RIGEX Top Plate and the vibe table adaptor plate and would have required removal of the structure from the vibe table to be checked. Back-out of the accessible bolts was not much of a problem with the X and Y axis tests. A few bolts were slightly loose but no obvious patterns arose. However, after the Z axis random vibration and *final* sine sweep tests were completed, the main interface bolt pattern between RIGEX and the bolt pattern adaptor plate was found to be noticeably loose. Countersunk lockwashers were used on this bolt pattern, as opposed to a combination of lockwashers paired with patchlock on all other structural bolts. After all of the 24 loose bolts were retightened, an obvious shift of the PSD peaks upwards, toward the *initial* PSD, was observed. Figure 4.10 shows an example of how tightening of the structure's bolts changed the PSD. An all-inclusive presentation of the *initial, final* and *repaired* PSDs is included in Appendix D for further reference.

Partial restoration of PSD shifts as a result of bolt retightening provided confidence in this test method and suggested that a downward shift of peaks after random vibration testing was due to bolt back-out. Uncorrected shifts in PSD peaks found in the *repaired* PSD were scrutinized further as possible culprits of additional damage.

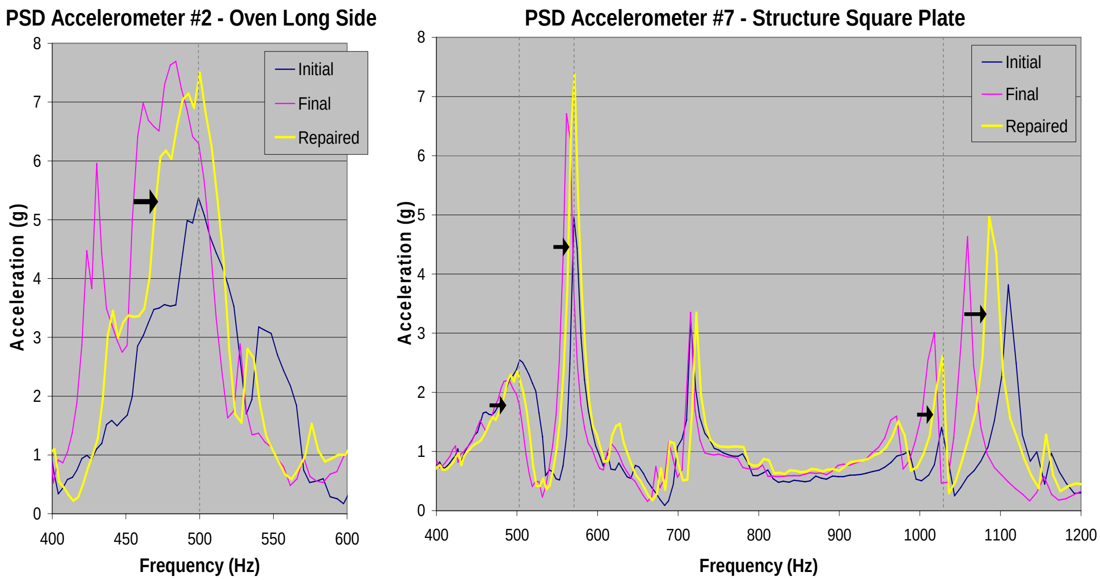


Figure 4.10 Shifts in Z Axis PSDs Observed After Retightening of Bolts

4.3.3 Dynamic Frequency Response Results

Appendix D includes all sine sweep PSDs generated from the Shuttle environment random vibration testing. The actual input levels achieved are also included in that appendix for further reference of the excitation levels that drove the results.

Some problems were encountered during Z axis testing. Although the sine sweep profile produced an acceptable set of data from all accelerometers, the vibration excitation system exceeded control limits during the random vibration test before reaching a full strength MEFL profile. High frequency noise, inherent in the system as soon as all components were powered on, was not controlled in the feedback loop. Therefore, vibrations in the high end range from 1800 to 2000 Hz repeatedly broke the alarm and abort limits before the full MEFL profile was reached. In order to complete testing of this axis, the profile was shortened to a range of 20 to 1860 Hz. Then, alarm and abort limits for the range between 600 and 1860 Hz were increased to ± 9dB and ± 12 dB respectively. At approximately 331 Hz a natural frequency of the setup was found to be uncontrollable as well. Therefore, a notch was placed in the profile from 322 to 340 Hz. These two modifications to the profile, while acceptable for AFIT driven prototype testing, are not allowed without specific permission when applied to acceptance level testing. Relaxing the alarm and abort tolerances, in this case, increased the overall acceleration level that the system was subjected to. Therefore, the profile changes were deemed acceptable because they increased the general strength of the profile. However, an added risk of over-testing was also incurred due to the changes. This altered profile and resultant excitation is shown in Figure D.20 of Appendix D.

X axis testing began once the vibe table setup was converted to the horizontal position and the software settings were modified, as detailed in the test setup. As anticipated, random vibration excitation with this test setup was more violent than the observed Z axis response. The RIGEX structure, essentially a cantilevered cylinder, combats Z axis axial loads very well. The first natural frequencies of the structure are bending modes triggered with X and Y axis excitation. Structural rocking along the ribs was visually apparent, albeit at very high frequencies, indicative of bending mode generation during horizontal testing. In the end, the structure successfully completed X axis testing and was rotated to align excitation with the Y axis.

During Y axis testing, visual inspection of the oven box assembly appeared promising. However, once the structure was removed from the sliptable to complete a visual assessment it became obvious that multiple bolts on the engineering model structure had failed. This damage, while unrelated to the oven assembly test objectives, must be kept in mind because it will affect all accelerometer results. Although it is reasonably straight-forward to identify structural damage following vibration testing, it is much more difficult to align specific structural damage with precise PSD changes. This type of sophisticated analysis requires a highly developed model, specific to the structure in question. Here only a general analysis, followed by visual inspection, was used to verify the structural integrity of the oven assembly. Figure 4.11 shows the areas where bolts failed along with a close-up of two bolt heads next to their detached threads that remained in the structure rib. In total, seven bolts failed; all due to shearing of the bolt heads from their shanks.

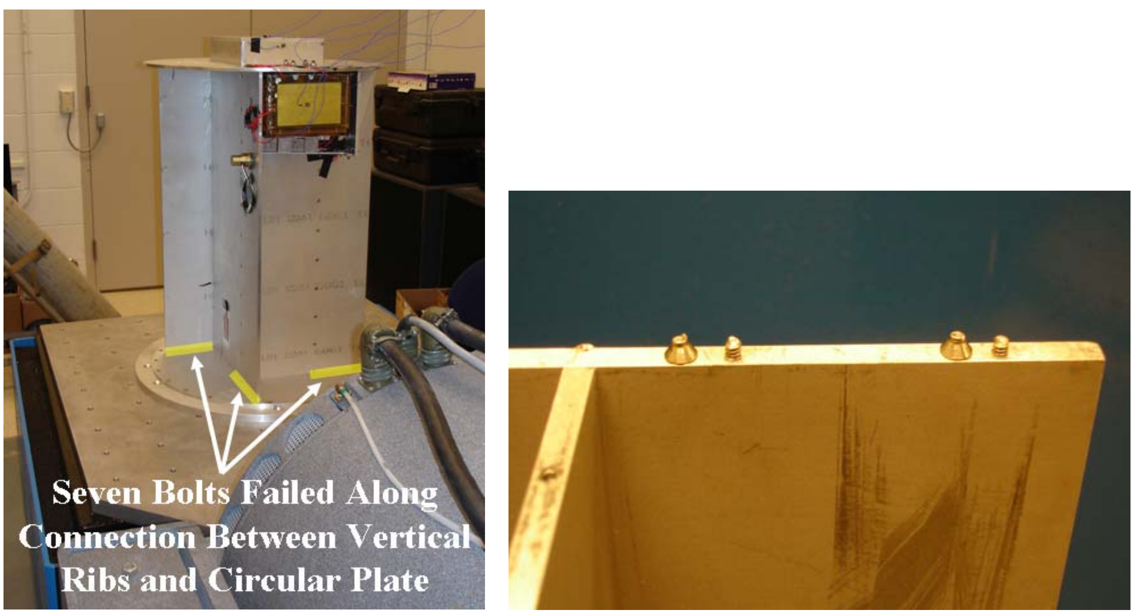


Figure 4.11 Location of Sheared Bolts and Close-up of Damage

4.3.4 Structural Health Monitoring Analysis

Random vibration testing of all three RIGEX axes was completed as described in the test setup. The data gathered from each axis tested was reviewed and analyzed. While some issues and concerns were presented, overall random vibration testing to verify structural integrity of the RIGEX oven assembly was completed successfully.

Z axis results showed evidence of damage due to loosening, or back-out, of bolts. The damage was corrected in the repaired PSDs as shown in Section 4.3.2. All other data from testing along this axis confirmed that minimal damage had occurred. As mentioned previously, the amplitude discrepancies were due to variations in amplitude of the excitation signal. This result can be observed by locating any area with varied amplitude in a PSD, noting the corresponding frequency, and then referencing the signal profile at that frequency. The sine sweep profile at any area of concern will show a difference in excitation input signal that correlates to the difference in amplitudes found in the PSDs. Some PSD change is anticipated due to settling of components. While proper assembly of components ideally produces a firm structure, in reality, all configurations will settle with age just as a building or brick wall does. As the components settle into their natural alignment due to a vibration environment, slight variations in dynamic frequency response will occur.

For the RIGEX structure, axial moments are created along the Z axis. It is clear from previous studies that the axial moments do not occur in the first set of natural frequency spikes, rather they only take place after a series of bending moments. The Z axis testing PSD graphs, Appendix D.3, reveal that the low frequency peaks do not change. The settling effect is only present in the mid to high frequency spikes, the peaks representing axial moments that would be effected by Z axis excitation. This point is driven home by data obtained from accelerometer #5 that was placed on the Sub-Tg tube flange. The tube is unique in that its first modes are not in bending like the rest of the structure. Rather, it acts like a slinky along the Z axis. Therefore, it is expected to exhibit axial moments before bending moments. Supporting this theory, the tube flange PSD showed settling shifts in the first set of peaks, unlike the other components of this structure. Observation of shifting in the higher frequency peaks for the EM structure paired with a shift in the low frequency peaks for the tube flange provides good indication that the root cause was settling of the components. Overall, the Z axis sine sweep – random vibration – sine sweep process was very informative and presented positive results supporting structural integrity of the oven assembly. The main concern arising from this set of data was bolt back-out. NASA requires two methods of back-out protection for all payload hardware. The flight model will use patchlock paired with preload, or torque, as its two methods. This solution should remedy the problem for future tests.

The X axis results shared many characteristics with those obtained from the Z axis. For example, the amplitude differences and shifts due to settling were the most prominent disturbances observed in the X axis random vibration data. Shifts were found in the first set of frequency spikes, this time due to settling from excitation of the bending modes by X axis random vibration. Overall, the responses were satisfactory and indicated structural settling rather than physical damage. The RIGEX structure bending modes do not align perfectly with the X or Y axes; rather, they are offset at an angle because of the unique positioning of the rib plates. Therefore, some amount of every bending moment will be detected with both X and Y axis excitation. That being said, the settling effect would be expected in the X axis testing but should fade out and be less prevalent in the subsequent Y axis tests because the same settling was already induced in the previous test. Also, bolt back-out was not as prevalent in this series of tests, indicating that excitation down the length of a bolt causes loosening more than excitation perpendicular to the bolt.

The Space Shuttle random vibration environment assessment was concluded upon completion of Y axis testing. Random vibration on the Y axis proved to overpower the RIGEX engineering model structure. After review of the PSD data it was apparent that many shifts between the *initial* and *final* were present. Furthermore, retightening of bolts only repaired some of the discrepancies. As reasoned earlier, after testing of the X axis fewer shifts due to settling were expected to prevail on the Y axis. Unfortunately, this was not the case.

A detailed visual assessment of the structure uncovered little damage initially. The oven assembly faired even better than expected because superficial damage from the Sub-Tg tube scratching the internal oven heaters during vibration was not present as anticipated. None of the oven assembly components failed, and all maintained the same composure with one exception. Some slight frictional damage was evident at the corners of the oven box flaps. The flaps were very tight-fitting and seemed to cement together at the corners producing small chips once the box was opened after test completion. This can be seen in Figure 4.12. The damage is slight and not considered critical. It was most likely due to rubbing of the flaps during random vibration resulting in frictional heat that caused the material to bind together.

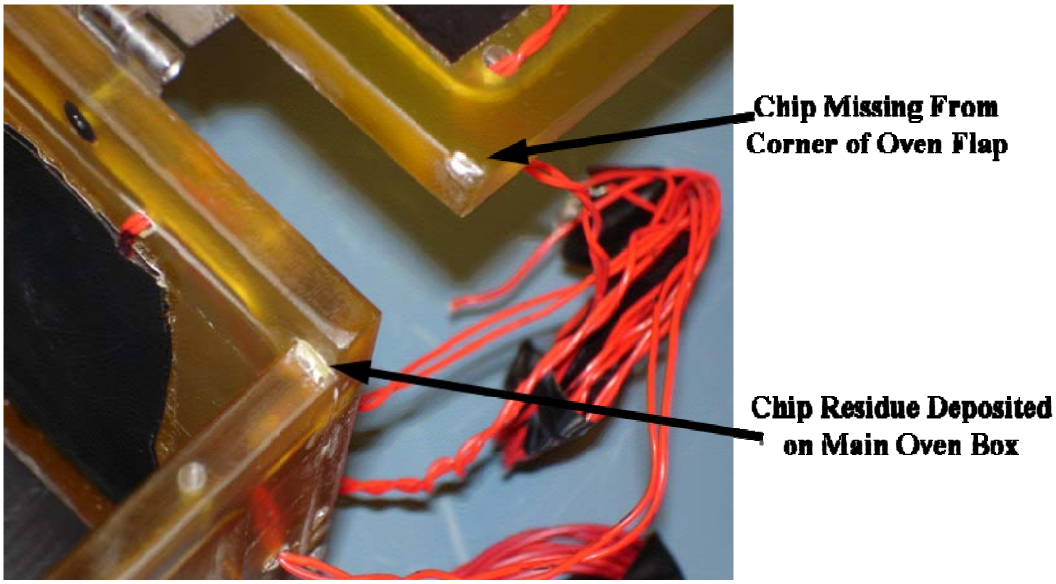


Figure 4.12   Friction Damage on Oven Box Flap

This friction-related damage to the oven box will cause some shift in the PSDs of accelerometers mounted to the box. However, the major cause of discrepancies in this round of testing was found when the RIGEX engineering model structure was taken off of the vibration table for examination. A set of bolts connecting the bottom circular plate to the rib plates were located between the circular plate and the vibe table adaptor plate. These bolts were sandwiched between two plates and, therefore, not accessible during the round of retightening before the *repaired* sine sweep was accomplished. Removal of the EM structure revealed that seven bolt heads were sheared off from the rest of the structure. The bolts that failed during Y axis random vibration testing were in the exact locations predicted by Holstein to incur maximum stress (16). This failure created a change in the boundary conditions of the entire structure and, therefore, had a great effect on the resultant PSDs. While changing the boundary condition can affect all frequency spikes, it is most evident in the first spike. Every accelerometer recorded a downward shift of the first peak. This shift is an indication of structural damage and can be associated with the bolt failure. Many peaks on the oven box accelerometers still aligned after this test and the visual inspection data was positive. This knowledge suggests that, while the engineering model structure failed, the oven assembly survived the Space Shuttle random vibration environment.

4.4 Summary

According to the CAPE Hardware Users Guide, the "CAPE/Payload will meet the random vibration flight levels specified in the Structural Verification Plan, with an analysis to the appropriate levels for flight" (6). In this chapter, the random vibration flight levels were specified and the test setup to was presented. Accelerometer data, with the aid of visual inspection, provided a set of results for analysis to determine the structural qualification of the oven assembly. In the end, structural verification of the prototype oven assembly was obtained. However, the RIGEX engineering model failed structurally due to shear failure of seven bolts. Modifications to the RIGEX structure since fabrication of the engineering model include adaptation to the CAPE canister, increased thickness of the aluminum plates, and larger bolts for structure assembly. The engineering model random vibration results add further assurance that the modifications already made were necessary. Random vibration testing created a wealth of knowledge concerning strength of the oven assembly, response of the structure to a Shuttle random vibration environment, use of the AFIT vibration laboratory equipment, and overall structural health monitoring methods via dynamic frequency response analysis.

V. RIGEX Structural Model Development

Development of the RIGEX structural model provides an analytical means for strength of material verification of the RIGEX design. Structural analysis, in the form of analytical calculations paired with physical hardware testing, is mandated by NASA and STP to ensure that RIGEX is structurally compatible with the NSTS (6, 24, 35). Additionally, this paired analysis is completed to prove that the combined CAPE/RIGEX payload will meet all of its mission objectives when subjected to NSTS flight loading conditions (35). NASA must be fully satisfied with the structural integrity of any proposed payload experiment in order for flight to take place. Without inclusive and accurate compliance with the factor of safety requirements, minimum natural frequency parameter, and design guidelines, NASA can delay or revoke launch of RIGEX on the Space Shuttle. Therefore, the methodology, model validation, model development, results and analysis of the RIGEX Finite Element Model (FEM) are presented in the following chapter.

The RIGEX FEM, or structural model, carries a dual purpose. First, eigenvalue analysis of the model will provide modal analysis to show that the minimum natural frequency parameter, delineated by the CAPE Hardware Users Guide (6), is met. Second, the model will be used for the analytical portion of structural strength verification. The structural strength will be assessed by applying various dynamic load conditions to the model, recording internal stresses, and then calculating material factors of safety to make sure that they exceed those required by NASA. Structural strength verification must be evaluated for both the structure's aluminum plate material and all fasteners holding them together. The scope of this thesis will include the eigenvalue analysis. However, the RIGEX FEM will be developed such that the structural strength verification can be completed at a later date.

5.1 Methodology

The main goal of the RIGEX FEM is to create a virtual model that will accurately represent the static and dynamic behavior of the true flight model structure. Therefore, a three-dimensional, deformable model of the main RIGEX structural elements must be put together. In its simplest form, RIGEX is an assembly of aluminum plates combined into a complex, cylinder-like geometry. The Finite Element Analysis (FEA) method is used to break down complex geometries into small elements which can then be assigned a simple spatial variation and solved numerically. FEA is an approximation tool, dating back to its inception in 1851, which provides "piecewise interpolation of a field quantity" that can then be reassembled in order to draw big picture conclusions (7).

In order to solve a problem with FEA, according to Robert D. Cook in *Concepts and Applications of Finite Element Analysis*, there are five main steps: problem classification, mathematical modeling, preliminary analysis, finite element analysis, and checking the results. These steps form a cyclical process that should be repeated until an adequate solution is found (7). Figure 5.1 illustrates the flow of the FEA process. For the RIGEX FEM as presented in this thesis, problem classification is included in section 5.2; mathematical modeling and preliminary analysis are discussed in section 5.3; final model development is in section 5.4; and the finite element analysis and results are presented in section 5.5.

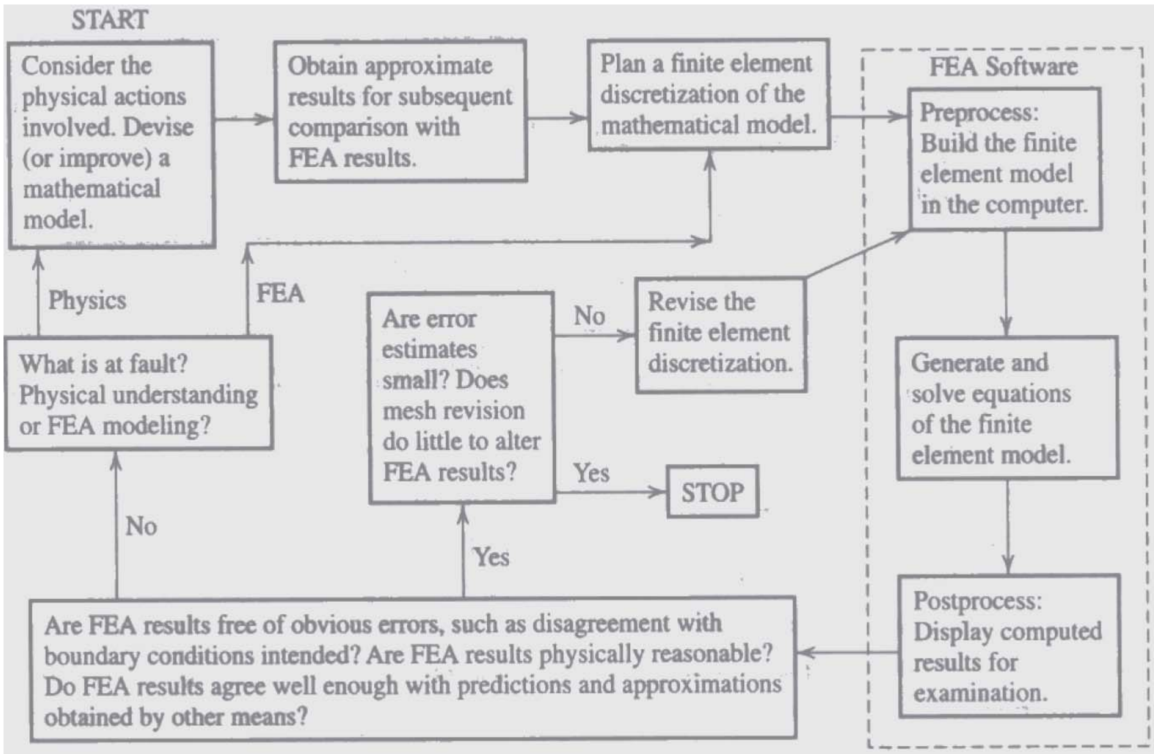


Figure 5.1 General Outline of a Finite Element Analysis Project (7)

With FEA, small groups of elements with simple applied loads and boundary conditions can be solved by hand. However, the computational complexity quickly escalates with added elements, complex geometries, compound loads, or refined boundary conditions. Therefore, FEA software programs are often used and widely available. FEMAP is a commercial finite element modeling and post-processing software analysis program that allows development of stress, temperature and dynamic performance analysis. In addition, *NX Nastran for FEMAP* "combines the power of the industry standard Nastran solver with the equally powerful modeling and post-processing capabilities of FEMAP" (11). This software combination has many capabilities that have proven to be very applicable to aerospace applications such as RIGEX. In fact, Nastran happens to be the first widely used FEA program, dating back to the 1960's, and was originally developed by NASA for its internal engineering community (33). For the RIGEX structural model, *NX Nastran for FEMAP* was utilized to dynamically solve for natural frequencies and mode shapes.

Natural frequencies are the frequency values at which a structure, when subjected to excitation at the frequency, is inclined to react. The mode shapes associated with each natural frequency define the deformed appearance of the structure as it is reacting, or vibrating (11). Computing a structure's natural frequencies and mode shapes involves a process called normal modes analysis, otherwise known as eigenvalue analysis. For this method, eigenvalues signify the natural frequencies and eigenvectors characterize the mode shapes. FEMAP solves for the undamped free vibrations of a structure using the following equation:

$$\left[[K]-\lambda_i[M]\right]\cdot\{\phi_i\}=0 \tag{1}$$

Where [K] is the structure's stiffness matrix and [M] is the structure's mass matrix. These matrices are determined by the geometry and properties applied in the structural model. The other two variables, λ_i and φ_i, are eigenvalues and corresponding eigenvectors that will be computed in the FEMAP software. From the resulting eigenvalues, the natural frequency values can be computed using the relationship

$f = \sqrt{\lambda_i}$ where f is the frequency in radians per second. There are many different solving methods for eigenvalue analysis. The Lanczos method will be applied to solve for the RIGEX FEM natural frequencies and mode shapes. This method provides robust results with a relatively small amount of required memory and fast calculation times (11). "Normal modes analysis forms the foundation for a thorough understanding of the dynamic characteristics of the structure" (11). This is due to the fact that eigenvalue analysis results are useful for a variety of applications and, most importantly, provide a straightforward baseline assessment of model confidence. If the natural frequencies and mode shapes presented in a FEM correlate well with physical test data, the FEM can then be used for other, more complicated analyses with a high confidence of obtaining realistic results. However, if eigenvalue analysis does not align with modal test data, then any results obtained from the model are of dubious validity.

Building a high fidelity model with appropriate element, meshing, and constraint choices is key in obtaining meaningful results. Therefore, a method of testing various models and their correlations to a physical specimen similar to the RIGEX structure was carried out. The modeling method that most closely resembles the test specimen results will be used to build the RIGEX FEM. This FEA approach validation will be accomplished using an available RIGEX engineering model structure as the test specimen and a set of *preliminary FEMs* as the computer models. The purpose of this portion of testing is two-fold. First, it will correlate a preliminary FEM with lab test data for FEA approach validation. Second, it will act as a FEMAP training tool to develop software proficiency for application on the final RIGEX FEM.

The step-by-step process for developing a finite element model starts with creating the geometry. In FEMAP this process involves employing an extensive set of options, such as shape, line, extrusion and solid tools, to draw the intended structure. Then, once each shape is drawn correctly, it is labeled as a boundary surface. By identifying each closed shape as a boundary surface, they are ready to be transformed from a geometry to a set of finite elements. This transition is made by meshing each surface with a set of nodes and elements. Each element consists of a connected group of nodes with assigned material properties. After the whole structure is meshed into a full finite element model and the model is checked for correct mesh alignment and material property values, analysis can begin. Many different analysis sets can be defined and saved in FEMAP, each with their own selected load and constraint sets. A load set defines what kind of load is applied to a structure, what the amplitude of the load is and which nodes it should effect. A constraint set tells the solver what type of boundary conditions to apply to the selected nodes. Once an analysis set is defined and chosen to run, the FEMAP software passes along all model and analysis set information to the NX Nastran solver for computation. The computed results of a successfully run analysis set are then passed back from NX Nastran into FEMAP for viewing. FEMAP provides many options for visual assessment of the results, along with a numerical data sheet that is recorded and saved from each test run for further reference. Finally, interpretation of the results and evaluation of their accuracy can then be completed.

For the RIGEX FEM, an analysis set to complete normal modes analysis with a constraint set of fixed nodes at the CAPE/RIGEX bolt pattern interface will be used. Applied loads sets are not used for normal modes analysis. Therefore, any stress or strain values developed from the analysis are strictly intended for differential location identification. The structural design goal is for the integrated CAPE/RIGEX payload to have a first natural frequency above 50 Hz (6). The root of this requirement comes from the NSTS 21000-IDD-SML document which states that all sidewall mounted payloads with a natural frequency less than 35 Hz must complete coupled loads analysis for all stages of flight (2). However, if the payload has a first natural frequency of greater than 35 Hz, with respect to the adapter interface, a table of limit load factors from NSTS 21000-IDD-SML can be used rather than having to complete coupled loads analysis. Therefore, CAPE requires that all of its payloads have a first natural frequency greater than 50 Hz in order to meet the 35 Hz cutoff for the whole integrated structure. From Holstein's previous analysis, it is known that the original RIGEX design met this requirement with a margin of almost 50 Hz. The updates and modification of RIGEX since then have made it a larger structure with thicker aluminum plates. Overall, the RIGEX structural design for integration with CAPE is much stiffer than the previous GAS can design. Therefore, the 50 Hz first mode qualification should be easily met. Furthermore, the first natural frequency is expected to go up from the predicted values in Holstein's work to indicate the added stiffness.

FEMAP is an incredibly valuable analysis tool if applied correctly. However, the graphical interface available within most FEA software makes it easy to develop complex models without understanding of the theory and internal calculations being used, leading to meaningless results. Knowledge of FEA theory and its associated assumptions and shortfalls is key to applying this powerful tool appropriately. For this reason, validation and verification of any FEA model is a necessary step in order to make use of the analysis results. For the RIGEX structural model validation, an initial set of preliminary FEMs were built to replicate the engineering model structure that was on hand in the lab. By developing a finite element representation of this structure in FEMAP, the normal modes analysis could be compared to hands-on lab testing results in order to confirm accurate modeling techniques. Then, the method for building the most accurate preliminary FEM will be applied to the RIGEX FEM with background confidence that the theory will be used correctly. The results of this approach validation testing are included in the section 5.3. Development of the RIGEX FEM is presented in section 5.4 and the results and analysis from normal modes testing of the model are included in section 5.5. First, however, a detailed description of the RIGEX FEM problem classification and all assumptions made for this series of finite element models are discussed in the following section.

5.2 RIGEX FEM Classification and Assumptions

The first step in developing a structural model is to understand the nature of the problem, otherwise known as problem classification (2). Background information on the specific problem delineates how to model, discretize, and analyze a structure. In addition, any simplifying assumptions made during the modeling process must be quantified for future reference. Finite element analysis is a simulation tool, not reality. Therefore, a mathematical model with generalized equations, and assumed conditions will give meaningful results only when paired with all the background information used to develop the model.

5.2.1 RIGEX FEM Problem Classification

The RIGEX structure is designed for spaceflight aboard the Space Shuttle. The structure is made of aluminum plates of various shapes and thicknesses formed into a generally cylindrical form. Many complex subsystems are held within the structure, but a detailed analysis of these items is not necessary because they are space qualified separately. However, their added mass to the structure does need to be taken into account. The strength of the structure under dynamic loading conditions and sufficient structural stiffness are the most important physical aspects involved. Nonlinearities from material properties are not allowed because yielding of the aluminum would be considered structural failure in this context. Natural frequency data and internal stress values are the two results sought from the RIGEX FEM analysis.

5.2.2 RIGEX FEM Assumptions

RIGEX is a complex structure; therefore, simplifying assumptions must be made in order to create a model that is computationally realistic. The following items will used as baseline assumptions for the development of the RIGEX FEM.

1. The RIGEX structure will be constructed entirely out of 6061-T651 plate aluminum. In FEMAP this material was assumed to be isotropic and homogeneous. In reality, there will be material imperfections present in any metal. However, prediction of such imperfections is impractical. The properties for this material were loaded from the FEMAP material library and were double-checked for accuracy with the values for 6061-T651 aluminum given in MIL-HDBK-5H (26). Table 5.1 lists the material properties for 6061-T651 aluminum used in FEMAP.

Table 5.1 Material Properties for 6061-T651 Plate Aluminum

Modulus of Elasticity	9900000 psi
Poisson's Ratio	0.33
Limit Stress, Tension	35000 psi
Limit Stress, Compression	35000 psi
Limit Stress, Shear	27000 psi
Mass Density	0.000253881 lbm per cubic inch

2. Various small holes for venting and wire routing are present in the RIGEX structure. These holes were considered to be a level of detail not required for FEM analysis and, therefore, were left out of the model. All of the surfaces in the RIGEX FEM are meshed as solid pieces with no cutouts present. The holes present in the flight model structure will reduce its mass and decrease its stiffness slightly.

3. A variety of subsystem components are housed within the RIGEX structure. The mass of these items must be addressed for an accurate FEM, however, analysis of the subsystem components themselves is not necessary. Therefore, these items were placed into the model as point masses. This treatment of the subsystem components makes inclusion of their added mass possible without any added stiffness to the structure. This is a conservative approach because, in fact, each component attached to the structure will add some small amount of stiffness to that area, as well as mass. Table 5.2 lists all of the RIGEX subsystem components that were included along with their weight and node number where the point mass was placed.

Table 5.2 List of Components Included in RIGEX FEM as Point Masses

	Weight (lbf)	Mass (lbm) *	Locator Node
Camera	0.62	0.001606	52, 62, 91
Computer	10.6	0.027455	757
Power Distribution Unit	11.1	0.028750	784
Fuse Box	2.6	0.006734	792
Cylinder Pressure Transducer	0.5	0.001295	207, 209, 212
Oven Mounting Bracket and Latch	0.71	0.001839	593, 631, 685
Heater Box + Sub-Tg Tube + Tube Pressure Transducer	2.75	0.007123	671, 680, 673
Total Added	28.88	0.074801	16 massed nodes

* using g = 386.0886 in / sec^2 for weight to mass conversion

4. In reference to the point masses included in the RIGEX FEM, other small masses were considered negligible with respect to the 0.375" aluminum plates and the over 150 pound total weight of the RIGEX structure. Therefore, any subsystem component weighing less than 0.25 pounds was not included in the model. Wiring was not included either because it was considered of negligible mass with respect to overall structural strength.

5. Nodes were individually created at the location of each bolt hole in order to represent accurate interaction between the plates. The bolt node was then tied to both adjoining surfaces. However, the detail of individual bolts and their respective bolt holes was not modeled. The stresses that result at bolt nodes can be used to derive the interaction of the actual bolt with the structure. Therefore, a node at each bolt location was considered to be sufficient detail for representation of the union of plates.

6. The CAPE Mounting Plate provides a mechanical interface between RIGEX and the CAPE canister. This plate is a 1.5" thick aluminum 6061-T651 circular disk with

a bolt pattern matching CAPE around the edge of its radius. The RIGEX Top Plate, 0.625” thick, is then attached to the CAPE Mounting Plate via another circular bolt pattern. The CAPE Mounting Plate was not included in the RIGEX FEM. The RIGEX Top Plate to CAPE Mounting Plate bolt pattern was assumed to be a set of fixed nodes, due to the extreme thickness of the CAPE Mounting Plate. As fixed nodes, there was no rotation or translation allowed in the model at these node locations. Therefore, the RIGEX FEM model was conservatively constrained in a fashion that allowed deformation of the Top Plate into the region where the CAPE Mounting Plate will be physically present. A trial run with Z axis translation constrained along the entire contact surface of the Top Plate was analyzed and found to be too much of a restriction, producing unrealistically stiff results. No solution was found that could restrict translation into the CAPE Mounting Plate while still allowing deformation away from the Mounting Plate. Therefore, the set of 28 fixed nodes representing the RIGEX Top Plate to CAPE Mounting Plate bolt pattern was implemented as the applied FEM constraint set.

5.3 FEM Method Validation Analysis

Finite element modeling has evolved into a multifaceted discipline. The theory has grown rapidly since the 1950s (7). Many commercial software packages exist and many modeling options are available. An assortment of element geometries and sizes, in two dimensional or solid three dimensional configurations, can be obtained. The shape functions assigned to a set of elements can be linear or quadratic, among other higher-order options, and the degrees of freedom which govern the spatial variation of a field can be added or taken away. Therefore, after problem classification is completed, an appropriate method for model development must be selected. The results produced by a model are largely dependant on its method of development; poor modeling choices will lead to fallacious results. A series of comparisons between laboratory test results and finite element model examples was completed in order to determine an acceptable modeling method to use for the RIGEX FEM.

5.3.1 Preliminary Model for Validation Analysis

An engineering model (EM) of the RIGEX structure was fabricated by previous students and available for use in the AFIT laboratory. This structure, shown in Figure 5.2, represents the design of RIGEX before it was modified for the CAPE container.

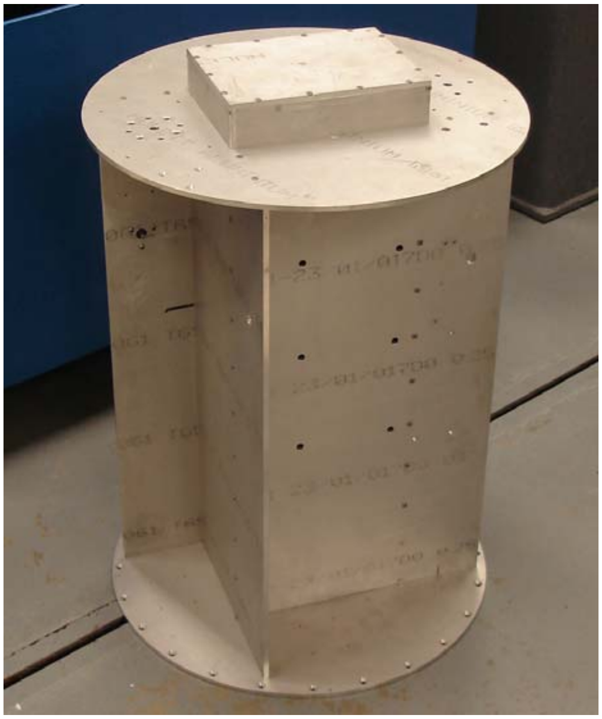


Figure 5.2 RIGEX Engineering Model Structure

Many changes have been made to the RIGEX structural design since the EM was built, including implementation of thicker aluminum plates and a larger cylinder radius. While the physical dimensions have been modified, the general make of the structure remained the same. The most recent RIGEX structural design is defined by detailed SolidWorks drawings, but has yet to be fabricated. The RIGEX structure is asymmetric and complex. It cannot be accurately represented by a simple cantilevered beam or cylinder because of the unique arrangement of structural rib plates. Therefore, the EM was used as a preliminary structure for validation of FEM methods because of its availability and similarity to the current design.

First, lab tests were completed to obtain natural frequency and basic mode shape data from the physical EM structure. These modal tests were completed before the EM structure was used for the Chapter 4 random vibration testing. Then, a series of FEMs representing the EM structure were built in FEMAP. These models are referred to as a set of *preliminary FEMs*, representative of the EM structure. As opposed to the *RIGEX FEM* which denotes the final FEM created, indicative of current RIGEX structural design. The main goal was to create a FEMAP model whose resultant eigenvalue analysis agreed with the natural frequency data found in the lab. Once found, the preliminary FEM method which best correlated with lab test data would be identified as the best method to use for the RIGEX FEM.

By determining methods of FEM construction that will accurately represent the natural modes of a physical test article, validation of modeling methods and FEM analysis for this specific problem is obtained. With confidence that the RIGEX FEM accurately represents how the structure will respond to external stimuli, the FEM can then be used to obtain natural frequency values and dynamic strength design validation.

5.3.2 FEMAP Preliminary FEMs

Two main models were built to represent the EM structure. The first model was created by forming solid rectangular and circular geometries with the correct dimensions and positions. Then this 3-D structure was meshed with solid parabolic elements. These elements were created using the FEMAP auto mesh function. Each element was a solid tetrahedral containing ten nodes. The second model was formed by placing 2-D shapes, without a visible thickness, in the proper positions to form the 3-D structure. Then, the same FEMAP auto mesh function was used to create a plate element mesh within each surface. The plate elements were four-noded quadrilaterals with some three-noded triangles present in areas with curved geometry. Figure 5.3 shows the structure of 2-D triangle (Tri) and quadrilateral (Quad) elements along with their 3-D tetrahedron (Tet) and hexahedron (Hex) counterparts.

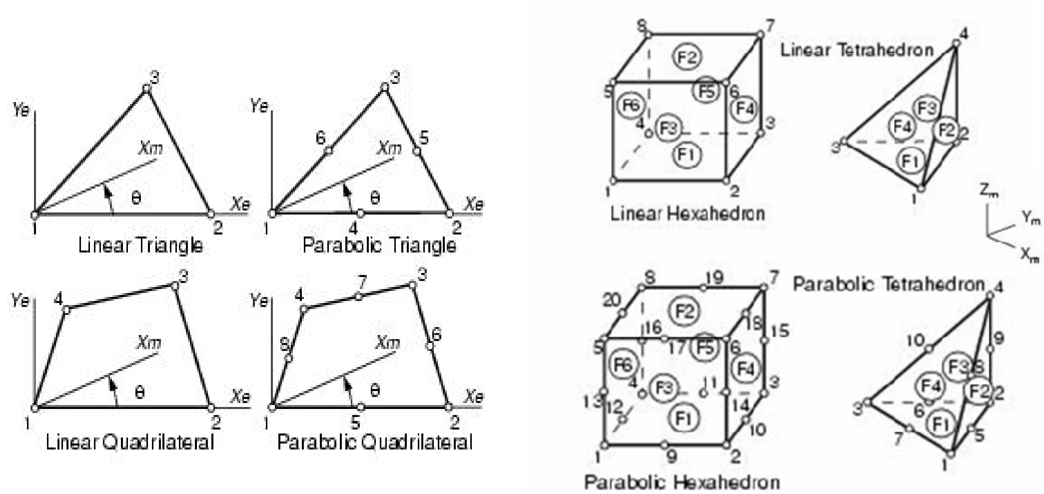


Figure 5.3 2-D (Tri and Quad) and 3-D (Tet and Hex) Elements (11)

Each element has a linear or parabolic option. The linear versions have nodes only at the corners of the element shapes and are characterized by a linear displacement field equation. The parabolic versions have an extra set of mid-side nodes spaced in-between each corner node. This allows the displacement field equations for these elements to contain a complete quadratic function.

Solid elements are known to have problems with locking when used in thin plates (7). Locking causes a model to exhibit high-stiffness behavior which, in turn, influences the analysis solutions. Convergence on an accurate answer can be obtained with refinement of the mesh. Still, this is an unattractive solution because of the significantly longer computation time (on the order of hours instead of minutes) taken to solve for densely populated 3-D meshes. 2-D plate elements have the ability to produce accurate results with fewer elements and a much smaller computation time, however, they will diverge from reality as the thickness of the plate being modeled increases. The entire RIGEX structure is composed of plates less than 1” thick. Therefore, plate elements are expected to exhibit relevant solutions with a coarse mesh while locking behavior in a solid model will skew results until an appropriately refined mesh is implemented. In the end, four preliminary FEMs were developed to represent the RIGEX engineering model structure. These models included one plate version, and coarse mesh, intermediate mesh, and fine mesh solid versions. An eigenvalue analysis of these four FEMs was completed with fixed node boundary conditions mimicking the circular bolt pattern of the EM structure in the lab. The first and second mode results from each model are contained in Figures 5.4 through 5.7. Each figure includes a color scale indicating the relative Von Mises stress distribution throughout the structure. The stress and displacement values shown are insignificant because eigenvalue analysis results are arbitrarily scaled in FEMAP for visual clarity. However, the mode shape and location were maximum stresses appear gives insight as to where the structure will be most harshly burdened during launch environment loading. Due to widely varied results of the different FEMs, lab testing was completed next to decipher which model had the highest aptitude for predicting RIGEX structural behavior.

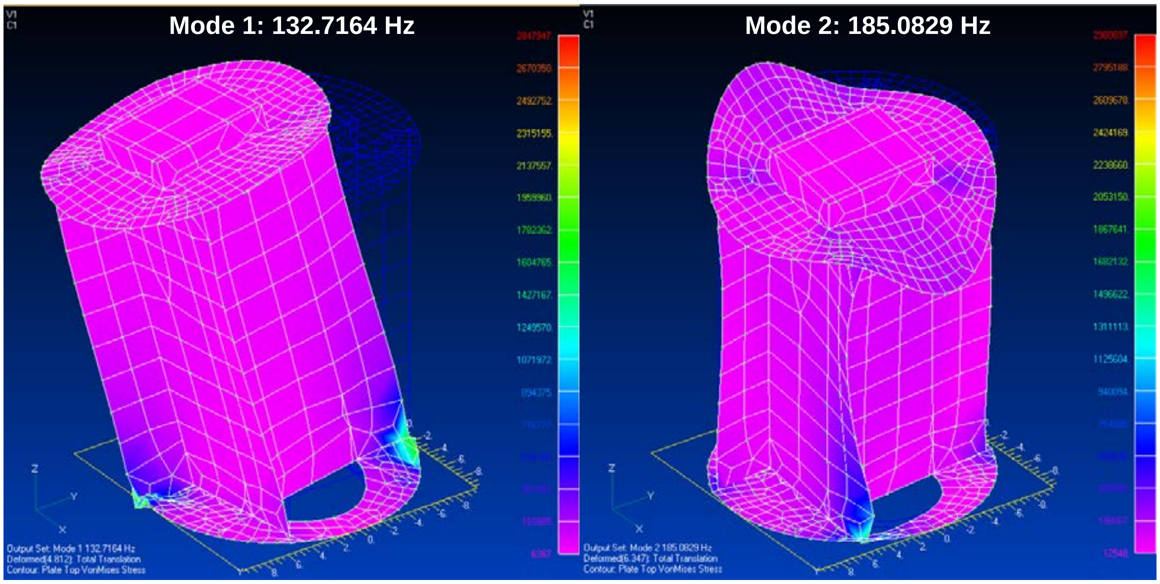


Figure 5.4 Plate Model – First and Second Mode Results

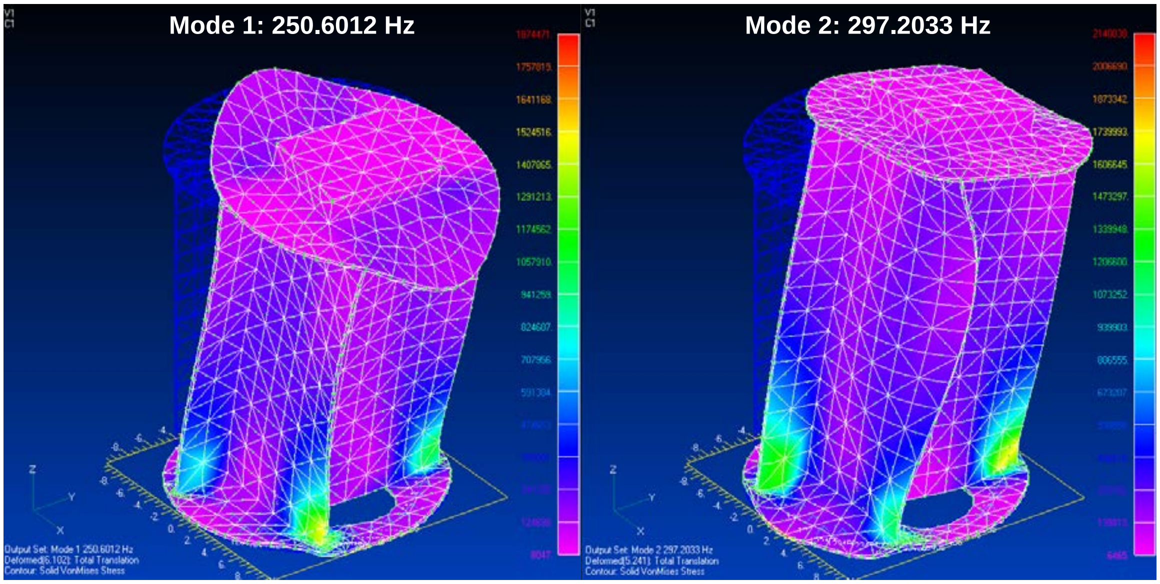


Figure 5.5 Coarse Mesh Solid Model – First and Second Mode Results

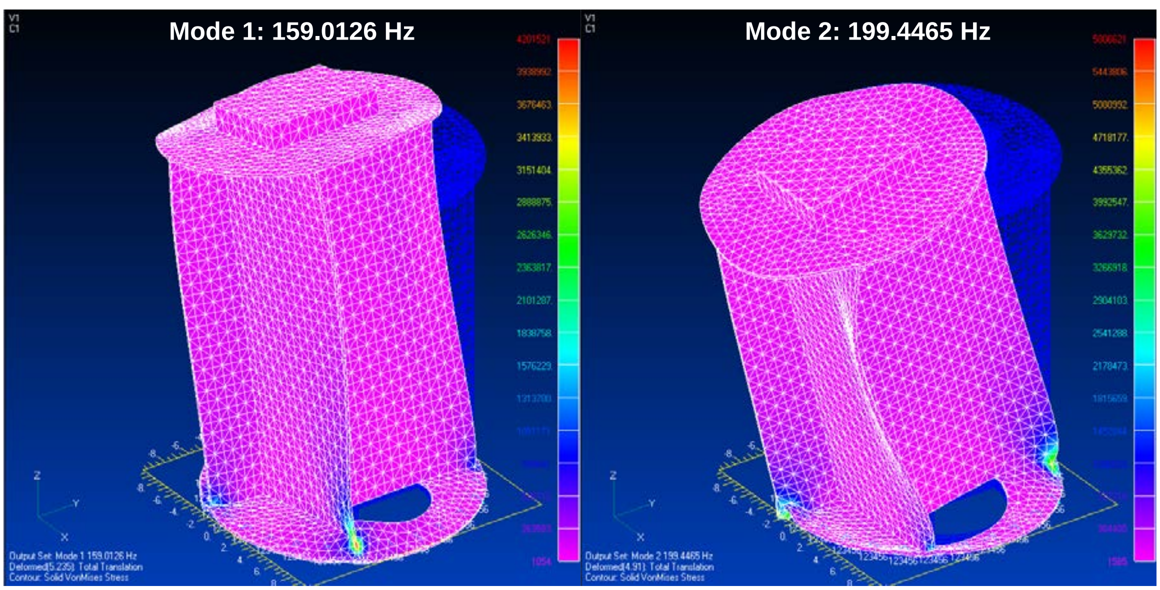


Figure 5.6 Intermediate Mesh Solid Model – First and Second Mode Results

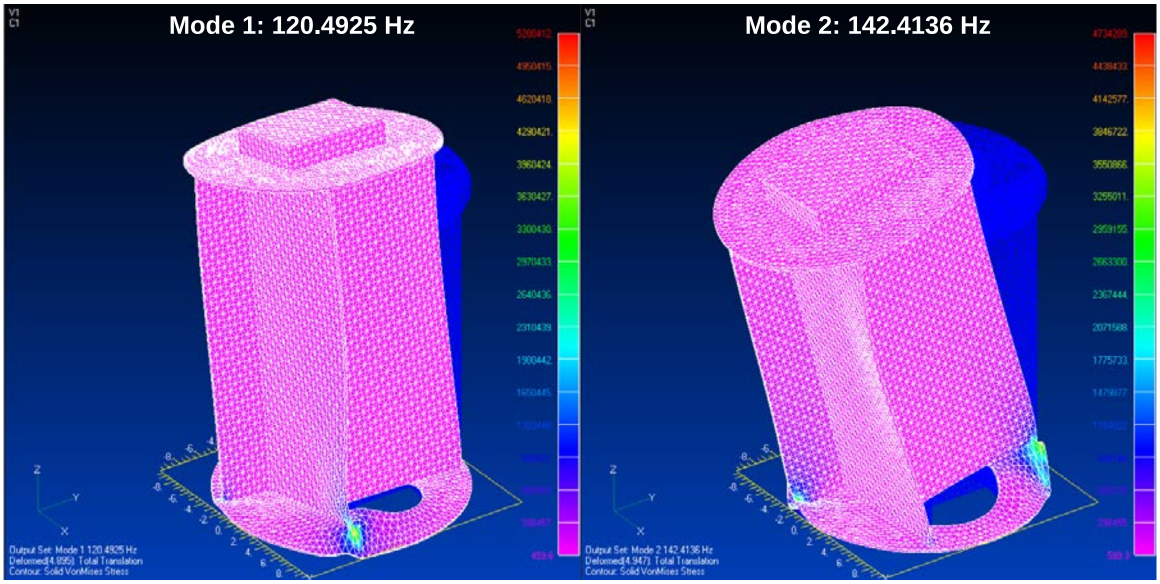


Figure 5.7   Fine Mesh Solid Model – First and Second Mode Results

5.3.3   Laboratory Testing of the RIGEX EM Structure

Baseline natural frequency values of the EM structure were obtained through ping testing and a 2-D laser vibrometer scan of the structure. The ping test setup is shown in Figure 5.8. SignalCalc software was used to gather data on the first two structure modes with a resolution of 1600 lines over a frequency span of 0-312 Hz. Three different accelerometers were placed at various positions to measure frequency response data from each hit of the ping hammer. Data was recorded when triggered by the ping hammer input voltage and 10 averages were used to produce the result graphs shown in Figure 5.9 (first bending mode) and 5.10 (second bending mode). These graphs also include coherence plots to assess the validity of the results over the frequency span.

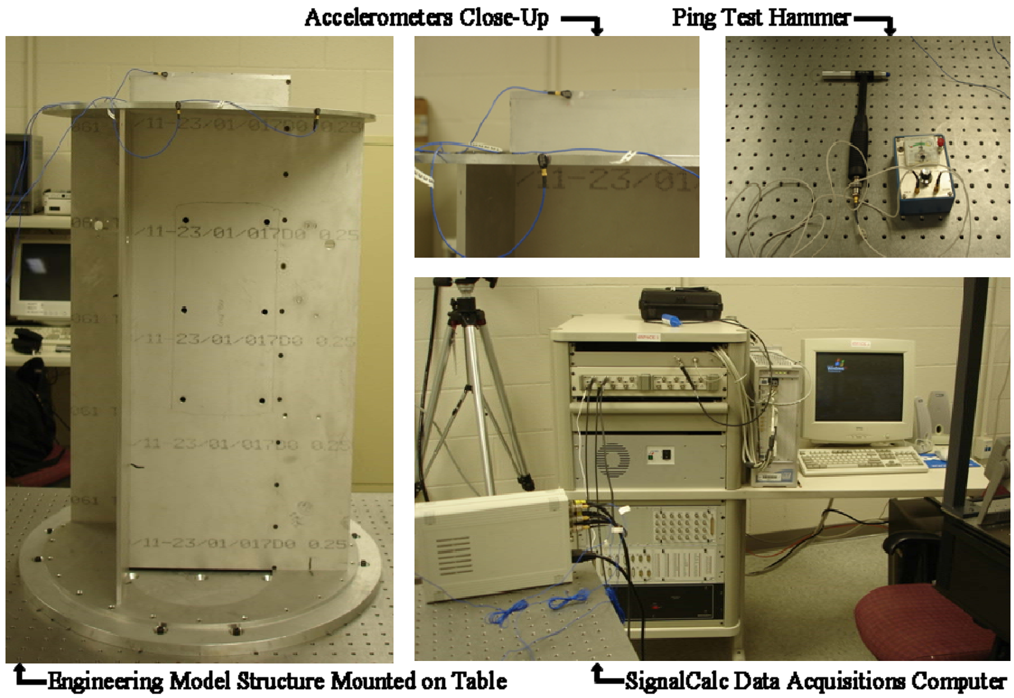


Figure 5.8 Engineering Model Ping Test Setup

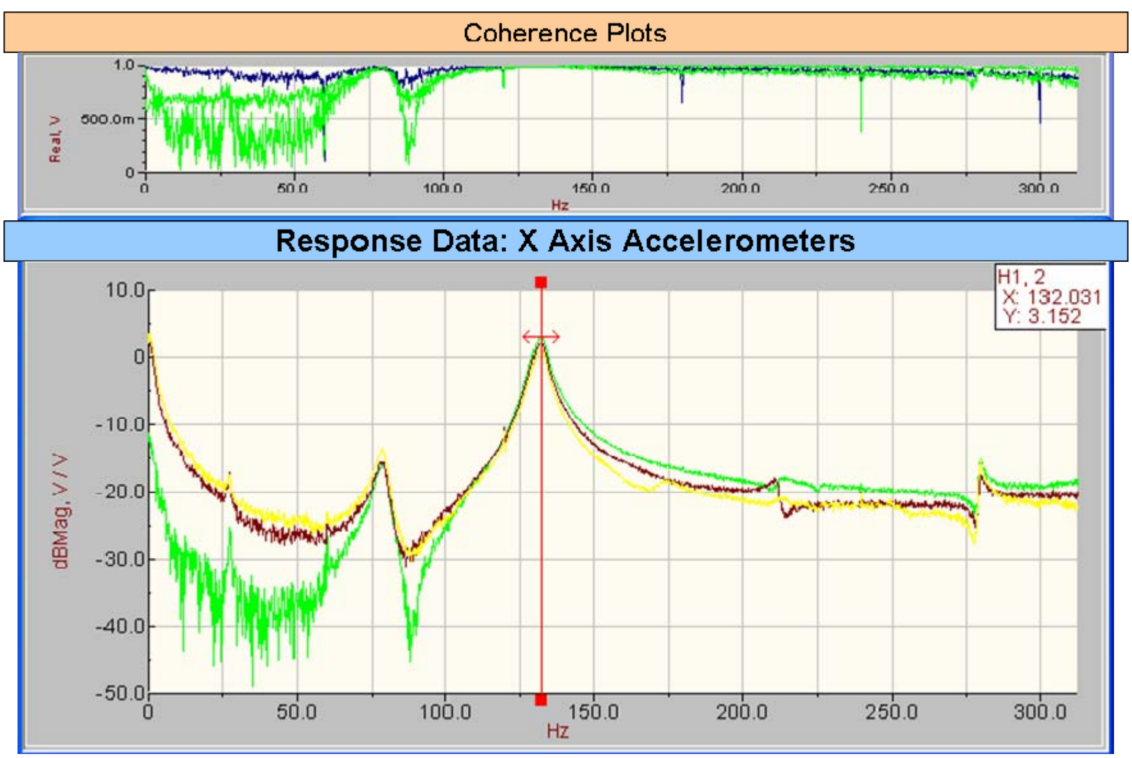


Figure 5.9 Engineering Model X Axis Ping Test Results, Mode One

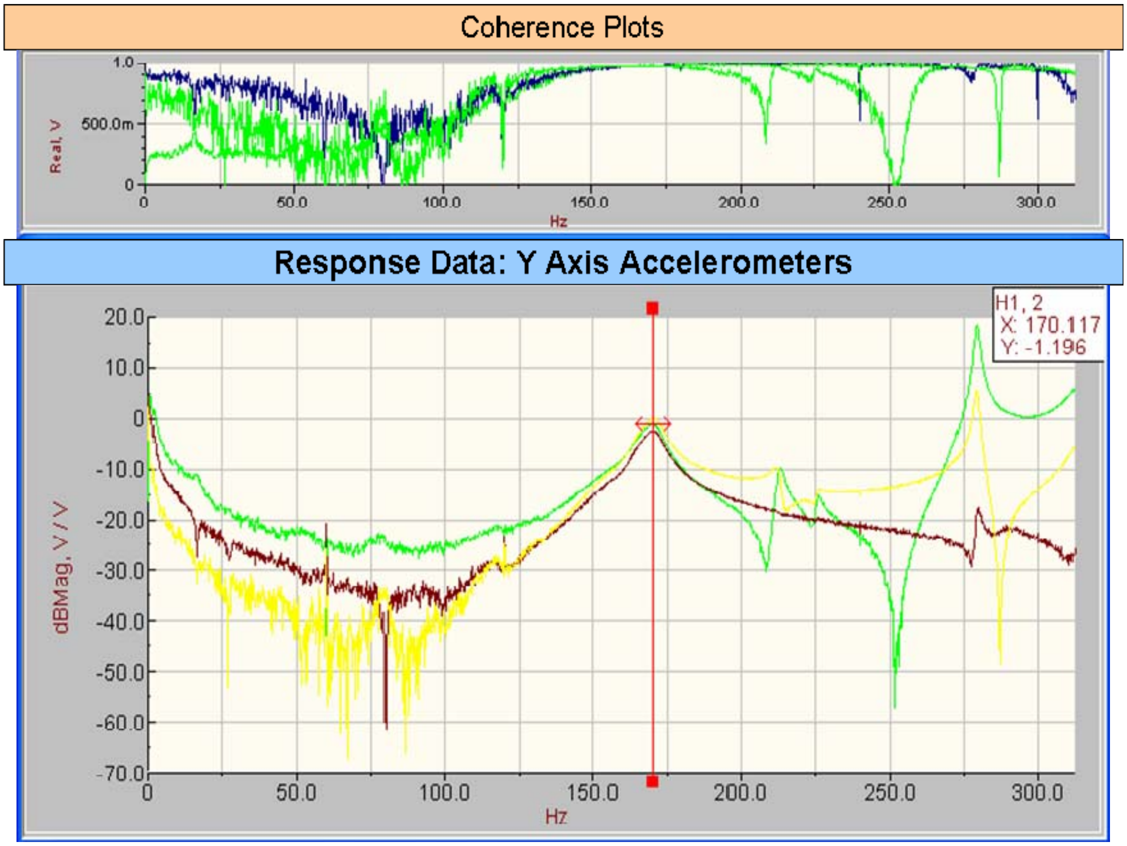


Figure 5.10 Engineering Model Y Axis Ping Test Results, Mode Two

Next, without moving the previous test setup, all accelerometers were removed and a 2-D scanning laser vibrometer was arranged to record modal data of the structure. Two forms of excitation were used to trigger a response: an acoustic horn and a piezoelectric PZT patch. Unfortunately, neither source provided enough input to the structure as a whole to produce clear results above the noise level. Peak values for modes one and two could be picked out, but only because the approximate values to search for were already deciphered from the ping test. The laser vibrometer technology proved to be a robust data acquisitions tool, however, results obtained from this specific test were sub-par due to the large size and stiffness of the EM structure with respect to the excitation input power. The laser vibrometer test setup can be seen in Figure 5.11. The X and Y axis results, focused on the area of interest from 60 to 200 Hz, are included in Figures 5.12 and 5.13.

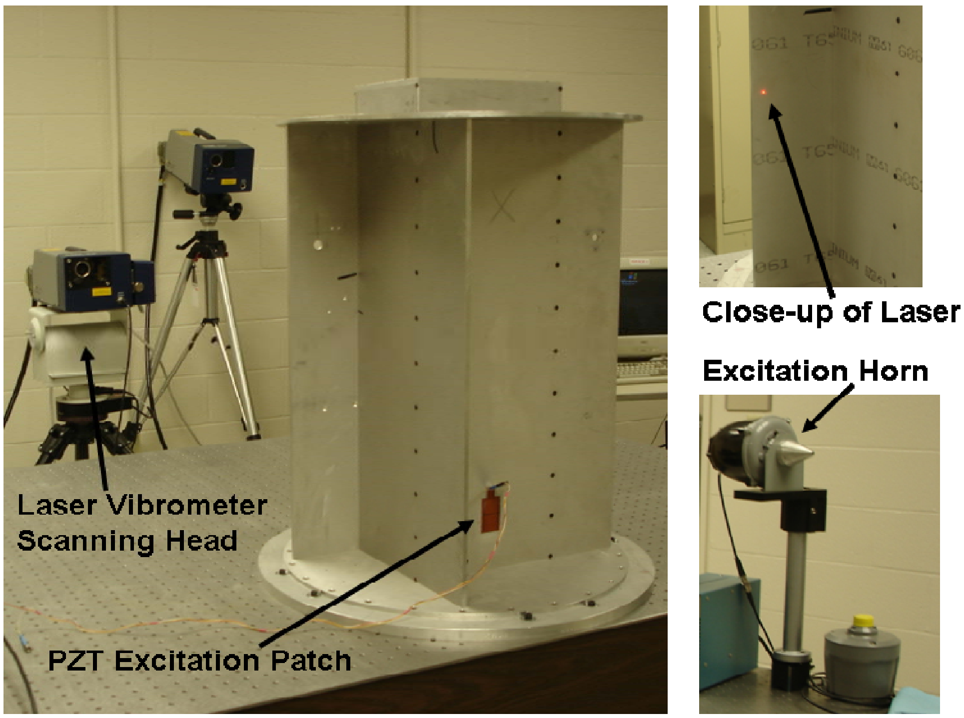


Figure 5.11   Laser Vibrometer Test Setup for Engineering Model Structure

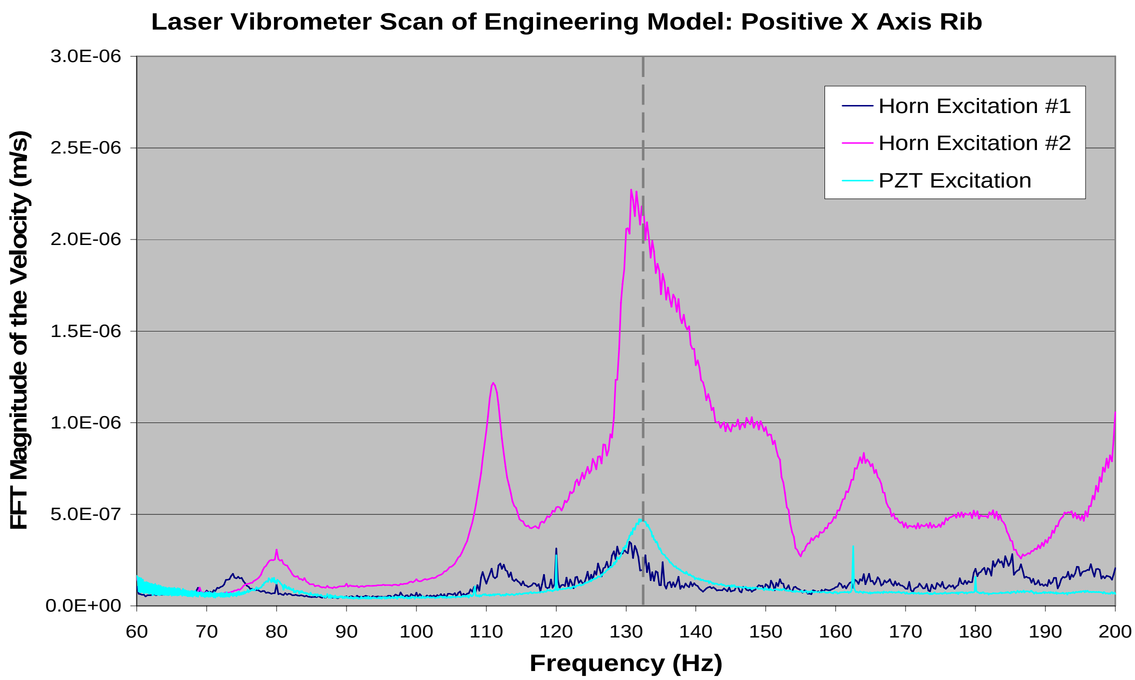


Figure 5.12   Engineering Model X Axis Laser Vibrometer Scan Results

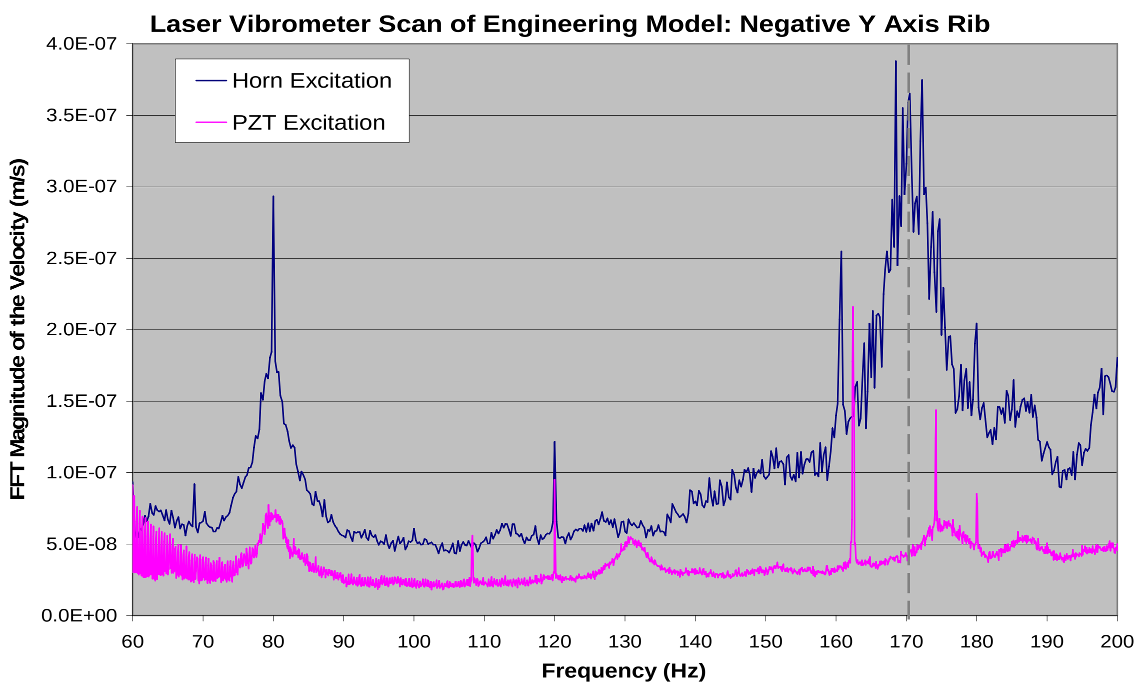


Figure 5.13   Engineering Model Y Axis Laser Vibrometer Scan Results

5.3.4 Validation Model Results and Conclusions

The set of data gathered in the lab, combined with eigenvalue analysis of the preliminary FEMs, provided an overall assessment of the EM structure. Table 5.3 includes a compilation of natural frequency results from all data sources mentioned, including thesis data developed by Holstein for the same RIGEX structure (16).

Table 5.3 Compilation of EM Structure Results for FEM Method Validation

Model Description	Mode 1 (Hz)	% Difference From Ping Test Results	Mode 2 (Hz)	% Difference From Ping Test Results
Ping Test	132		170.1	
Laser Vibrometer Scan	131.5	-0.38%	170.5	0.24%
FEMAP 2-D Linear Plate Model	132.7	0.53%	185.1	8.82%
FEMAP 3-D/Solid Quadratic Coarse Mesh	250.6	89.85%	297.2	74.72%
FEMAP 3-D/Solid Quadratic Intermediate Mesh	159	20.45%	199.4	17.23%
FEMAP 3-D/Solid Quadratic Fine Mesh	120.5	-8.71%	142.4	-16.28%
Holstein, 2004 - ABAQUS Linear Plate Model *** Incorrect Configuration ***	178	34.85%	-	-
Holstein, 2004 - ABAQUS Quadratic Plate Model	148.17	12.25%	192.69	13.28%
Holstein, 2004 - ABAQUS 3-D/Solid Quadratic Model	113.84	-13.76%	131.82	-22.50%
Holstein, 2004 Ping Test of Empty Structure	94	-28.79%	-	-

The ping test gave very clear, concise results and, therefore, was used as a baseline *truth* comparison for all other data in the percent difference column. The solid meshes exhibited locking behavior, as expected, and improved with mesh refinement. Analysis of the 3-D/Solid Quadratic Fine Mesh FEM took over an hour to complete.

This is an unrealistic amount of time considering that the Shuttle loads analysis for structural integrity involves over 60 different load set combinations. The plate model analysis ran in under 60 seconds and resulted in the most accurate natural frequencies.

The addition of Holstein's model information sheds further light onto the subject. His ping test data differs from the data presented here. This is most likely due to the fact that he attached the EM structure to the vibe head extender for testing, see Figure 4.6 for identification of the vibe head extender. The extender was then placed on the lab floor, held down only by its own weight. Holstein's setup provided a much lighter boundary condition compared to the large table used in the present work, and also added to the length of the cantilevered structure. Both of these differences would decrease the stiffness of the test structure, overall, and cause the first natural frequency to decrease in comparison to the test included herein. Furthermore, the boundary conditions used for FEM analysis, in both the FEMAP and ABAQUS models, represent perfectly fixed nodal constraints, a very stiff restraint. It is thus reasonable to conclude that the ping test with a stiffer physical boundary condition, the one used in this thesis, should provide more accurate results for comparison to the FEMs.

Another main point must be taken into consideration when drawing conclusions from Table 5.3. The FEMAP linear plate model closely represented the ping test *truth* data. However, in Holstein's analysis the opposite conclusion was drawn when his 3-D solid models showed a closer fit to his lab data. Upon closer investigation, it was found that his 2-D ABAQUS models represented RIGEX as a structure with clockwise rotating ribs. The 3-D ABAQUS models show a structure with counterclockwise rotating ribs, the true RIGEX and EM structure configuration. Figure 5.14 shows the difference between Holstein's two models. The variation between models occurred because the plate model was created very early on in the design process. Then, the orientation of the plate design was flipped and the 3-D model was developed to reflect the change. The inconsistency between models could account for some of the result discrepancies due to the unsymmetrical nature of the structure.

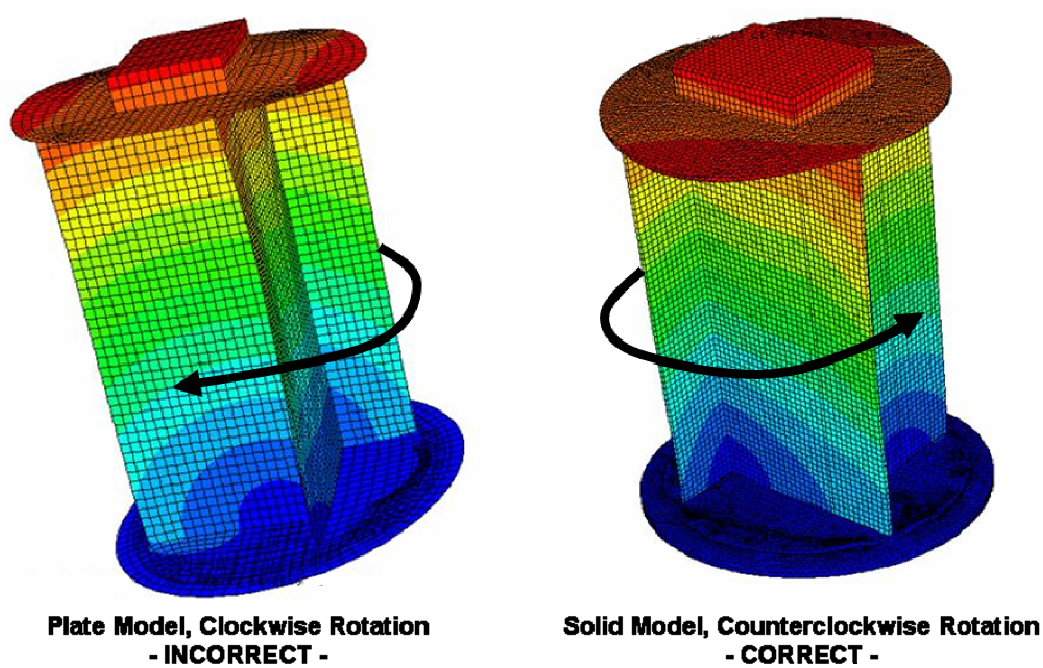


Figure 5.14 Correct vs. Incorrect RIGEX Configuration from Holstein's Work

The final conclusion drawn from this series of method validation trials was to employ a plate FEM. The plate elements had many advantages over solids including fewer elements and nodes, shorter computation times, and more accurate results without refining of the mesh. With large elements permitted, a plate model RIGEX FEM could be built with nodes only placed at the bolt locations. This allows for analysis at bolt hole locations without having to average stress values over a series of included elements. Each stress value will be drawn straight from the model outputs to determine bolt factors of safety. In summary, the plate model approach to finite element modeling and analysis will be used, with confidence, in the following section to develop a final RIGEX FEM.

5.4 RIGEX FEM Design

Once validation of an FEM method was done, the final RIGEX structural model could be created. This endeavor began with formation of the proper geometry in FEMAP. The RIGEX structure is composed of ten aluminum plates: a top plate, two inflation system mounting plates, four ribs, an oven mounting plate, bottom square plate and a shroud. Each shape was drawn separately according to the dimensions specified in the RIGEX drawing package. These detailed drawings, made in SolidWorks, can be found in Goodwin's thesis (14). A point was placed at each bolt location to represent accurate connections between the plates. Points were also placed at the center of mass positions for each subsystem component to use later as point mass locators. After all boundary surfaces and points were placed, three custom meshing options were designated. First, a *meshing attribute* was chosen to define the material property and plate thickness of each surface. The rib plates, pressure system plates and square bottom plate are all made of 0.375" thick 6061-T651 aluminum. The top plate and oven mounting plate were both made of a thicker 0.625" 6061-T651 aluminum. Then, a *custom mesh pattern* was specified along each surface edge. This was to ensure only one element lay between each bolt hole connecting the plates. Finally, the *mesh points on surface* command was utilized to guarantee that nodes be planted on all bolt and point mass locations within the outline of each surface. With these three specialized options applied to each plate surface, the geometry was ready to be transformed into a finite element model.

Each surface was meshed separately in order to form the RIGEX FEM. After a surface was meshed, the element and nodes it included were recorded. Then the section had to be checked for coincident nodes in order to tie together adjacent plates. Each coincident node was merged by hand so that proper alignment and interaction would occur. When possible, the model was meshed with linear Quad elements. However, linear Tri elements populated the entire top plate and oven mounting plate to create a better fit due to their circular geometries. A unique set of three tube elements was also included in the RIGEX FEM. These elements were included to represent the three inflation system pressure cylinders, sandwiched between the two structural inflation system plates. Insertion of the tube elements represented reality by tying together the two physically separated inflation system plates. The last basic item included in the RIGEX FEM was a boundary condition of nodal constraints. A cutaway view of the RIGEX FEM is shown in Figure 5.15 to show the pressure cylinder tube elements and the fixed bolt pattern constraints.

Eigenvalue analysis of the RIGEX FEM was completed for four different structural conditions. These conditions were un-massed without shroud, un-massed with shroud, massed without shroud, and massed with shroud. A property card for each subsystem component was formed with the correct mass included. Then a mass element was applied to each nodes corresponding to a subsystem location. The shroud was created by extrusion of a curve from the Top Plate to the Oven Mounting Plate. These two items were removed and added to create the four structural conditions for eigenvalue analysis in NX Nastran.

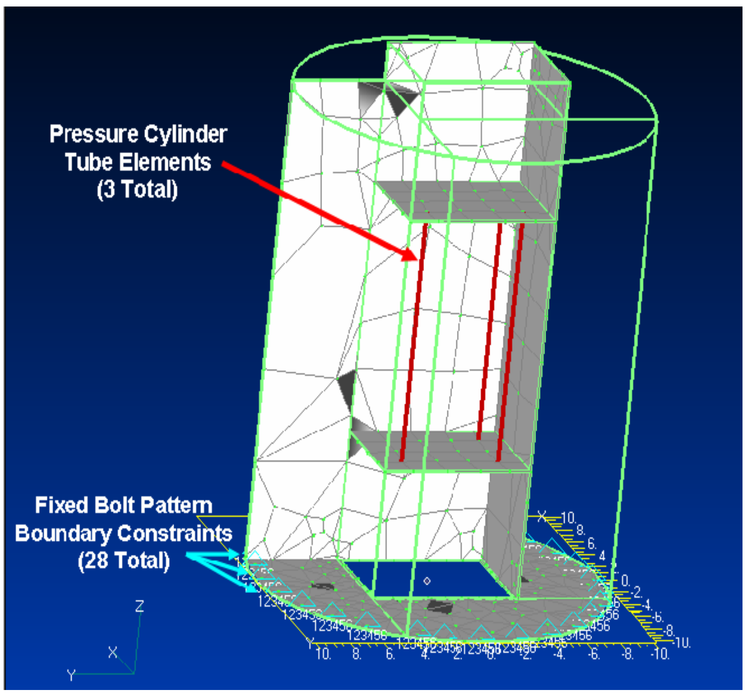


Figure 5.15 Cutaway View of the RIGEX FEM to Show Internal Components

5.5 Results and Analysis

The results from the RIGEX FEM, included in Table 5.4, were as expected. Including the shroud showed an added stiffness with increased natural frequency results.

Whereas, inclusion of point masses decreased the values illustrating their effect of added weight without structural stiffness. Also, as expected, the RIGEX FEM presented higher natural frequencies than the EM structure. The first mode of the full massed structure with shroud included came out to be 242 Hz. This is well above the 50 Hz first mode limit set by STP. Figure 5.16 shows this primary mode shape of the full RIGEX FEM. Appendix E includes the mode shape results from all four model configurations.

Table 5.4 RIGEX FEM Natural Frequency Results (Hz)

	Mode #1	*Mode #2*	*Mode #3*	*Mode #4*	*Mode #5*
1. Un-Massed Structure Without Shroud	**183.2516**	**229.7479**	**246.8618**	**264.0316**	**297.364**
2. Un-Massed Structure With Shroud	**291.9092**	**308.4555**	**348.5955**	**360.2367**	**369.3506**
difference between 2 and 1	108.6576	78.7076	101.7337	96.2051	71.9866
3. Massed Structure Without Shroud	**154.3872**	**194.047**	**233.1935**	**244.703**	**260.0337**
difference between 3 and 1	-28.8644	-35.7009	-13.6683	-19.3286	-37.3303
4. Massed Structure With Shroud	**241.979**	**264.0233**	**345.5232**	**356.3005**	**366.4316**
difference between 4 and 2	-49.9302	-44.4322	-3.0723	-3.9362	-2.919
difference between 4 and 3	87.5918	69.9763	112.3297	111.5975	106.3979

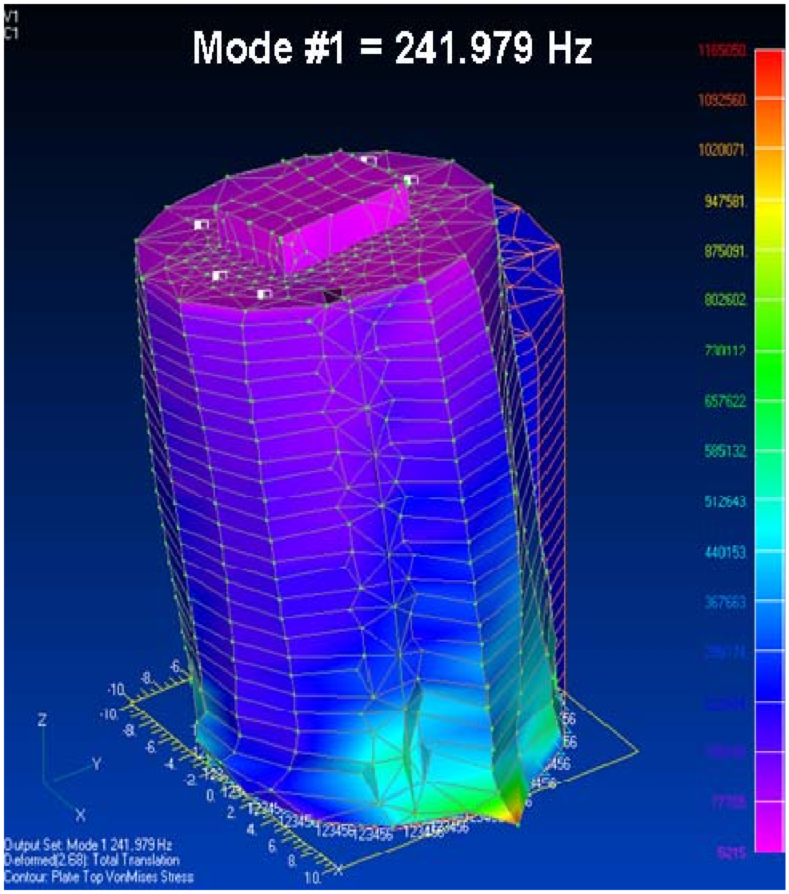


Figure 5.16   First Mode Results – Full RIGEX FEM

5.6   Summary

Finite element modeling and analysis are powerful payload risk mitigation tools to ensure adequate strength of design. Development of the RIGEX structural model began with Holstein's thesis work in 2004. However, modification of RIGEX in the form of thicker plates and a larger radius compelled a new RIGEX model to be built. Through extensive testing and analysis of the EM structure and a set of *preliminary FEMs*, confidence in the RIGEX FEM results was obtained. A first natural frequency of approximately 242 Hz was determined for the RIGEX flight model. Analytical FEM documentation, along with future flight model acceptance testing, will provide AFIT and STP with adequate structural verification data for launch. The final RIGEX FEM, massed structure with shroud, will continue to be used for loads analysis and modal frequency comparison until all NASA requirements are met.

VI. Conclusions and Recommendations

The Rigidizable Inflatable Get-Away-Special Experiment concept was developed in 2001 and now its design is quickly approaching finalization. As the payload design matured, launch integration began. The launch requirements and documentation process for integration of RIGEX onto the Space Shuttle was discussed in Chapter III. Part of this process includes a series of structural verification analyses. Two components of structural verification were documented within this thesis. First, prototype testing of the RIGEX oven assembly under the Space Shuttle random vibration environment was completed and documented in Chapter IV. Second, development of the RIGEX structural model, via a finite element model, was presented in Chapter V. This closing chapter will include a final discussion of the conclusions and recommendations due to all work presented in this thesis.

6.1 Launch Requirements and Documentation

Many of the initial steps in the Space Shuttle launch integration process have been completed over the last two years. RIGEX belongs to the Air Force Institute of Technology and, consequently, is a Department of Defense payload. The Space Test Program manages all DoD payloads that are to be launched on NASA's Space Shuttle. Therefore, the launch integration process consists of AFIT-STP-NASA coordination. The main topics included within launch integration are the payload design development, safety documentation and review process, and a set of payload specific integration documentation.

6.1.1 Conclusions

RIGEX is on track for launch in 2007. However, there are still many milestones to complete before RIGEX is cleared for integration onto the Shuttle. The next big step is finalization of the RIGEX design in preparation for the CDR, currently scheduled for early April 2006. This review is much more stringent than the PDR and requires a complete detailed design. After this review, fabrication of the flight model can begin.

The majority of the remaining integration items are related to NASA safety requirements. The Phase II Safety Review, scheduled for early May 2006, will define the extent of RIGEX testing and documentation to be done along with a specific timeline for successful completion. The major takeaway from Chapter III is that launching an experiment into space is a very involved process and, especially with the manned Space Shuttle vehicle, many parties are concerned with the safety qualifications of the payload.

6.1.2 Recommendations

Continued interaction with STP personnel is critical for RIGEX success. They provide a vast wealth of knowledge and have access to NASA resources not available directly to AFIT students. Weekly teleconferences have taken place between the AFIT team and STP. This weekly communication will become more important as the launch date nears and, therefore, should be continued. Also, as much overlap between incoming and outgoing graduate students as possible should be allowed for continuity purposes.

While intensive knowledge of NASA documentation and guidelines was not a necessity for initial RIGEX design, the current status requires continual consultation with these documents. Therefore, all students should be familiar with the wealth of NASA documents available along with the databases of previous payload designs. A NASA publication exists to address every step along the path to a successful payload launch aboard the Shuttle.

6.2 Shuttle Environment Random Vibration Testing

The random vibration environment produced during Space Shuttle flight can be damaging to payloads if not sufficiently designed. Therefore, laboratory testing of payload structures is done in order to verify their strength under the unique loading conditions present during the most demanding portion of the flight, the launch phase. These tests provide results to conclude proper experiment function and payload safety during flight. Chapter IV presented information detailing the methodology, test setup, results and analysis of the random vibration prototype testing of the RIGEX oven assembly. The random vibration test conclusions and recommendations discussed here will bring this thesis topic to a close.

6.2.1 Conclusions

The RIGEX oven assembly prototype test, conducted in the AFIT vibrations laboratory, provided supporting evidence to conclude that the assembly will survive the Space Shuttle random vibration environment and perform as designed during Sub-Tg tube inflation. First, verification of the structural monitoring method was shown via proof of repeatability and observation of repair. Repeatability was proven through matching PSD results due to two successive Z axis sine sweep tests. Also, once a PSD shift was identified after the Z axis random vibration test, all accessible structure bolts were retightened and a *repaired* sine sweep was completed. This third sine sweep test showed a significant improvement in the results, moving the PSDs back toward their *initial* sweep positions. While unplanned, bolt back-out after the first random vibration test provided a very good example of what structural health monitoring via dynamic frequency response analysis can identify. The ability to fix the damage due to bolt back-out and, thus, return a PSD back to its original form is a concrete demonstration of how the method works.

Furthermore, the oven assembly survived random vibration testing on all three orthogonal axes. The data analyses showed structural failure of the RIGEX engineering model, but no critical damage to the oven assembly was revealed. Modification to the oven flaps in order to relieve friction damage due to random vibration should be completed. However, no critical structure alterations need to be made.

6.2.2 Recommendations

Completion of prototype random vibration testing suggested a slight adjustment to the oven box flaps and a series of recommendations for future vibration testing. The oven box flap modification should consist of two main actions. First, each oven should be checked for proper fit of the flaps before integration onto the flight model. Proper fit includes the two flaps lined together in the closed position, touching each other. However, they should not be snug or need to be forced into the closed position. These conditions indicate too tight of a fit and could cause undue friction and binding during launch, as shown in Figure 4.10. Second, the edge of the oven flap that is attached via a hinge to the main box should be rounded. Rounding the flap edge will further prevent improper fit and eliminate chipping without degrading the integrity of the box structure. These two modifications will improve oven assembly design and addresses the results from this set of prototype testing.

The AFIT electrodynamic vibration table was used to complete a successful series of oven assembly prototype tests. However, certain aspects of its operation were highlighted along the way due to unsatisfactory performance if applied to flight model acceptance testing. These items include substandard feedback control of the excitation profile and the presence of high-end noise during Z axis tests. Also, two test setup items implemented for prototype testing need to be changed for acceptance testing. These items include specifying torque values for every bolt used on the vibe table and correct mounting of the text fixture to mimic true flight configuration.

The substandard feedback control of the vibe table occurred when alarm limits were breached at times during testing. Exceeding this limit was acceptable for prototype testing, but represents a ±3 dB, or 50%, deviation from the target profile. NASA Technical Standard Document 7001 identifies a list of acceptable test control tolerances. These tolerances are: ±10% composite rms acceleration, ±5% acceleration spectral density (25 Hz or less frequency bandwidth resolution), ±5% frequency, and +10%, -0% test duration (33). An investigation of the MB Dynamics software and hardware options must be accomplished in order to determine how to implement these tolerances levels on the AFIT equipment. Two sets of signal driving software are available in the laboratory. The MB Dynamics software was used for the prototype testing. However, if its control algorithm cannot support tolerances this tight, switching to the available Puma software control system could be a potential solution.

The high-end noise problem with the Z axis test configuration must be remedied before future testing can be accomplished. The vibe table must be able to produce a successful random vibration profile within the profile tolerances and throughout the full test duration. The risk of failure due to over testing was allowed during prototype testing; however, it is not an option when dealing with flight model hardware. The risk during acceptance testing is too great because any structural failure could lead to a slip in the launch date or cancellation altogether. In order to combat this risk, two things must be done. Identification and elimination of the high-end noise source is the first item and a bare resonance survey from 10 to 2000 Hz prior to integration of each component for vibration testing is the second. The sine sweep survey will identify any problems, systematically, as the test configuration is built up. According to NASA, "if practical, the fixture shall have no resonances within the test frequency range" (33). If any resonances are found during the pretest surveys, notching of the profile should be applied. Notching, or force limiting, "provides a rational and economical solution to the overtesting problem associated with hard mounting of test items, while still providing high confidence in the capability of the hardware to survive the mission vibroacoustic environments" (33). Integration of the RIGEX flight model for acceptance testing should begin only after a pretest assessment of the vibe table hardware and software is successfully carried out.

The last two recommendations for future random vibration testing involve hardware setup of the test article. For more accurate and conclusive testing, the damage due to bolt back-out should be eliminated. This will be inherently addressed during acceptance testing because flight model hardware will be used and assembly procedures will be followed. Flight model procedures must involve specified torque values for each bolt, strict adherence to the torque value applied, and a set of high quality torque wrenches and hex driver sockets with which to apply the torque. Currently, many of the necessary assembly tools are not available in the AFIT vibration laboratory and should be procured before flight model assembly. A detailed list of tools required for assembly should be included as an addendum to the list of flight model fasteners. This list also belongs as an attachment to the assembly procedures. Finally, the last recommended change for random vibration acceptance testing involves the configuration used to mate RIGEX to the vibe table. The NASA directive for mating a payload test article to a vibe table is to use flight equivalent mounting and fasteners (33). Therefore, some form of adaptor ring to mimic the CAPE to RIGEX mounting configuration needs to be designed. Discussion with STP about this topic and how previous payloads have approached the problem has already begun. This dialogue should continue until a satisfactory conclusion is agreed upon by both parties.

Overall, the lessons learned from this first use of the AFIT electrodynamic vibration exciter should be taken and applied to future testing endeavors. Fluid interaction with STP and NASA about RIGEX testing methods should continue because each payload will have its own concerns along the way. Therefore, flexibility is built into the process as long as evaluation of any payload specific tailoring is approved by all parties involved along the way (33).

6.3 RIGEX Structural Model Development

Finite element modeling is a powerful tool when properly applied. FEMs can look correct in physical appearance but, depending on the internal theory applied, obtain a variety of widely divergent results. Therefore, a series of method validation tests were done on the RIGEX EM structure to decipher an appropriate modeling method for the RIGEX FEM. The method used to build the most accurate preliminary FEM, a linear plate model, was then applied to the RIGEX FEM. Therefore, a plate model RIGEX FEM was constructed and analyzed in NX Nastran for FEMAP software and produced reasonable, validated results. This section contains the conclusions and recommendations substantiated from the RIGEX finite element modeling and analysis study.

6.3.1 Conclusions

The RIGEX FEM produced reasonable results. These results can be quantitatively assessed once the RIGEX flight model is assembled and tested in the lab. For now, the claim of model accuracy is based on method validation via EM lab data compared with a set of preliminary FEMs. The mode shapes and frequencies obtained from eigenvalue analysis mimicked the hypothesis of bending modes before axial or torsion modes and a higher first frequency to confirm the increased stiffness from structure modifications. Also, the first natural frequency of 242 Hz easily meets the STP minimum first modal frequency requirement of 50 Hz, as expected. The information presented in this document supports the plan to continue use of the full RIGEX FEM (massed with shroud) for load analysis. With Shuttle loads applied, the RIGEX FEM will produce valuable information about the strengths and weaknesses inherent with the current structural design.

6.3.2 Recommendations

The cyclic intent of FEM design will come into play when the RIGEX flight model is built and undergoes acceptance testing. Then lab data for the exact structure represented in the RIGEX FEM will become available. Correlation with the acceptance test results will provide an opportunity for revision of the RIGEX FEM. If the results clash, then refinement and modification of the RIGEX FEM should be done until it accurately represents the physical specimen. Per the *Payload Verification Requirements* document, NSTS 14046, an analytical model should match test result to within 5% of the primary modes and 10% of the secondary modes (32). This standard should be used to show a sufficient quantitative assessment of the RIGEX FEM when compared to lab data. After RIGEX FEM eigenvalue analysis data matches the lab test results, the Shuttle loads analysis should be assessed. Table 6.1 values can be used as the load factors because the first natural frequency of RIGEX is above 50 Hz (2). The load analysis can be done before flight model acceptance testing to gain insight for experiment design. However, a reassessment of the load analyses to show sustained applicability after the FEM is validated should be done as well.

Table 6.1 Sidewall Mounted Payload Limit Load Factors (2)

FLIGHT EVENT	LOAD FACTOR g			ANGULAR ACCELERATION RAD/SEC^2		
	N_x	N_y	N_z	$\ddot{\phi}_x$	$\ddot{\theta}_y$	$\ddot{\Psi}_z$
LIFT-OFF						
Low Frequency	±7	±7	±6	±75	±20	±55
Vibration	±5.4	±8.0	±5.4			
Combination (RSS on One Axis at a Time) 1	±8.8	±7	±6	±75	±20	±55
2	±7	±10.6	±6	±75	±20	±55
3	±7	±7	±8.1	±75	±20	±55
LANDING	±6	±7	±8	±85	±30	±50

Although it is beyond the scope of this thesis, the RIGEX FEM developed herein will eventually be used to assess internal structural stresses due to Space Shuttle flight environments. Once internal stress values are calculated from the FEM, they will be analyzed according to the respective material strengths. Then, the resultant factors of safety must show margins greater than those listed in Table 6.2 (39). Also, a preloaded bolt analysis must be completed, with application of maximum internal stress on each bolt pattern found by the RIGEX FEM, to ensure that the bolt factors of safety are greater than those designated in Table 6.3 (39).

Table 6.2 Minimum Design and Test Factors for Metallic Structures (39)

Verification Approach	Ultimate Design Factor	Yield Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	1.4	1.0 *	1.4	NA or 1.05 **
Protoflight	1.4	1.25	NA	1.2

NOTES:
* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.
** Propellant tanks and solid rocket motor cases only.

Table 6.3 Minimum Design and Test Factors for Fasteners and Preloaded Joints (39)

Verification Approach	Design Factors			Test Factors	
	Ultimate Strength	Joint Separation		Qualification	Acceptance or Proof
		Safety Critical *	Other		
Prototype	1.4	1.4	1.2	1.4	NA
Protoflight	1.4	1.4	1.2	NA	1.2

NOTE:
* Joints that maintain pressures and/or hazardous materials in a safety-critical application.

6.4 Summary

This thesis presented the launch integration and structural verification progress that has been accomplished for the Rigidizable, Inflatable Get-Away-Special Experiment since its manifestation as a CAPE payload on the Space Shuttle. Timely development of RIGEX for an on-schedule launch was made by accomplishment of the following items:

1) The PDR and Phase 0/I SR were successfully completed. Preparation for the upcoming CDR in April 2006 is underway as well.

2) Prototype random vibration testing of the RIGEX oven assembly validated its structural integrity and provided some minor modifications for improved flight performance.

3) A RIGEX FEM was created using FEMAP software. Eigenvalue analysis of the model showed a margin of over 90 Hz with respect to the required first modal frequency minimum. The model can now be applied to Shuttle flight loads analysis for further structural verification assessment.

Many current satellite technology concepts involve the use of large space structures that are limited by launch vehicle size and weight constraints. Inflatable, rigidizable structures can "potentially revolutionize the design and applications of large space structural systems" (17). Development and launch of the RIGEX payload will increase knowledge of inflatable, rigidizable structures by providing on-orbit reliability data and an assessment of ground test methods for future applications.

Appendix A: Preliminary Design Review Presentation

The following briefing was presented by the RIGEX team at AFIT to a group from the Air Force Space Test Program on 20 September 2005. This presentation fulfilled the requirement to meet Preliminary Design Review standards as an initial step in the launch integration process.

Rigidizable Inflatable Get-Away-Special Experiment (RIGEX)

Preliminary Design Review

20 September 2005

U.S. AIR FORCE

SPACE TEST PROGRAM

PATHFINDER FOR DoD SPACE SYSTEMS

Integrity - Service - Excellence

U.S. AIR FORCE

Agenda

0800-0815 Welcome	1100-1110 Break
0815-0830 STP Introduction	1110-1130 Electrical Power Subsystem
0830-0845 AFIT Introduction	1130-1200 Command & Data Handling Subsystem
0845-0900 Mission Definition	1200-1300 Lunch
0900-0915 Experiment Overview	1300-1330 Lab Tour
0915-0930 System Configuration	1330-1400 Test & Evaluation
0930-0940 Break	1400-1415 Mission Operations
0940-1000 Mechanical Subsystem	1415-1430 Program Management
1000-1030 Inflation Subsystem	1430-1500 Wrap-up / Action Items
1030-1100 Thermal Subsystem	

RIGEX Preliminary Design Review 2

Contents

1 Introduction
- 1.1 Purpose
- 1.2 Administrivia
- 1.3 Organization
- 1.4 Objectives
- 1.5 PDR Reference Documents

2 Mission Definition
- 2.1 Mission Objectives
- 2.2 Work Breakdown Structure
- 2.3 Operational Requirements and Restraints

3 Experiment Overview
- 3.1 Concept
- 3.2 Key Components
- 3.3 Justification
- 3.4 Instrumentation

4 System Configuration
- 4.1 Physical Configuration
- 4.2 Coordinate Systems
- 4.3 Equipment List
- 4.4 Mass Properties
- 4.5 Configuration Issues

5 Mechanical Subsystem
- 5.1 System Specifications
- 5.2 Status
- 5.3 Mechanical GSE
- 5.4 Open Issues

6 Inflation Subsystem
- 6.1 System Specifications
- 6.2 Physical Configuration
- 6.3 Block Diagram
- 6.4 Status
- 6.5 Open Issues

7 Thermal Subsystem
- 7.1 System Specifications
- 7.2 Status
- 7.3 Open Issues

8 Electrical Power Subsystem
- 8.1 System Specifications
- 8.2 Status
- 8.3 Open Issues

9 Command & Data Handling / Flight Software Subsystem
- 9.1 System Specifications
- 9.2 Status
- 9.3 Open Issues

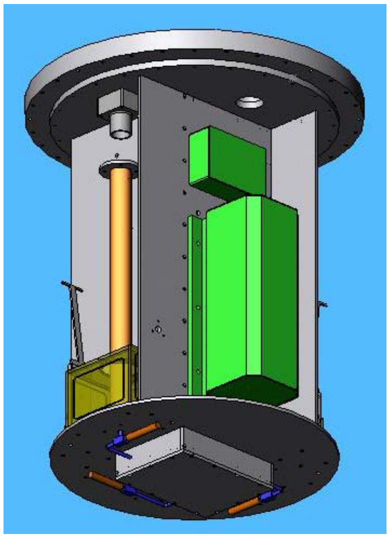
10 Test and Evaluation
- 10.1 RIGEX History
- 10.2 Future Tests
- 10.3 Status
- 10.4 Open Issues

11 Mission Operations
- 11.1 Mission Ops Concept
- 11.2 Ground Ops
- 11.3 Open Issues

12 Program Management
- 12.1 Master Schedule
- 12.2 Risk Areas
- 12.3 STP Documentation
- 12.4 Safety Documentation
- 12.5 ICD Discussion

1. Introduction

- 1.1 Purpose
- 1.2 Administrivia
- 1.3 Organization
- 1.4 Objectives
- 1.5 PDR Reference Documents

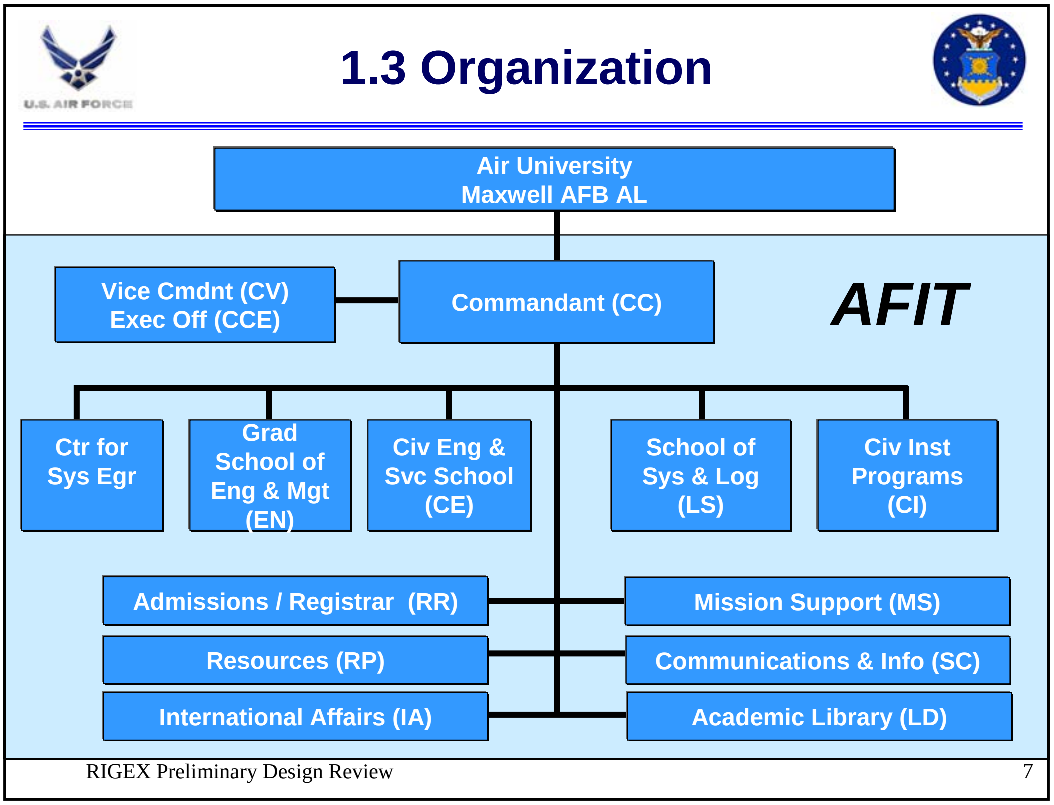


1.1 Purpose

- First major milestone of progress between AFIT and STP
- Define and document design and configuration baseline
- Coordinate design and operational issues with STP team
- Review launch vehicle interface requirements and state of compliance
- Describe and agree upon current and planned testing
- Review analyses to verify that the design meets Shuttle requirements
- Discuss areas of risk
- Identify potential design/safety issues
- Provide tour of lab and hardware
- Illustrate progress and provide future plans
- Review program master schedule

1.2 Administrivia

- Rest rooms
- Fire evacuation route
- Action item forms
- Lunch orders


1.3 Organization
U.S. AIR FORCE
Air University
Maxwell AFB AL
AFIT
Vice Cmdnt (CV)
Exec Off (CCE)
Commandant (CC)
Ctr for
Sys Egr
Grad
School of
Eng & Mgt
(EN)
Civ Eng &
Svc School
(CE)
School of
Sys & Log
(LS)
Civ Inst
Programs
(CI)
Admissions / Registrar (RR)
Mission Support (MS)
Resources (RP)
Communications & Info (SC)
International Affairs (IA)
Academic Library (LD)
RIGEX Preliminary Design Review
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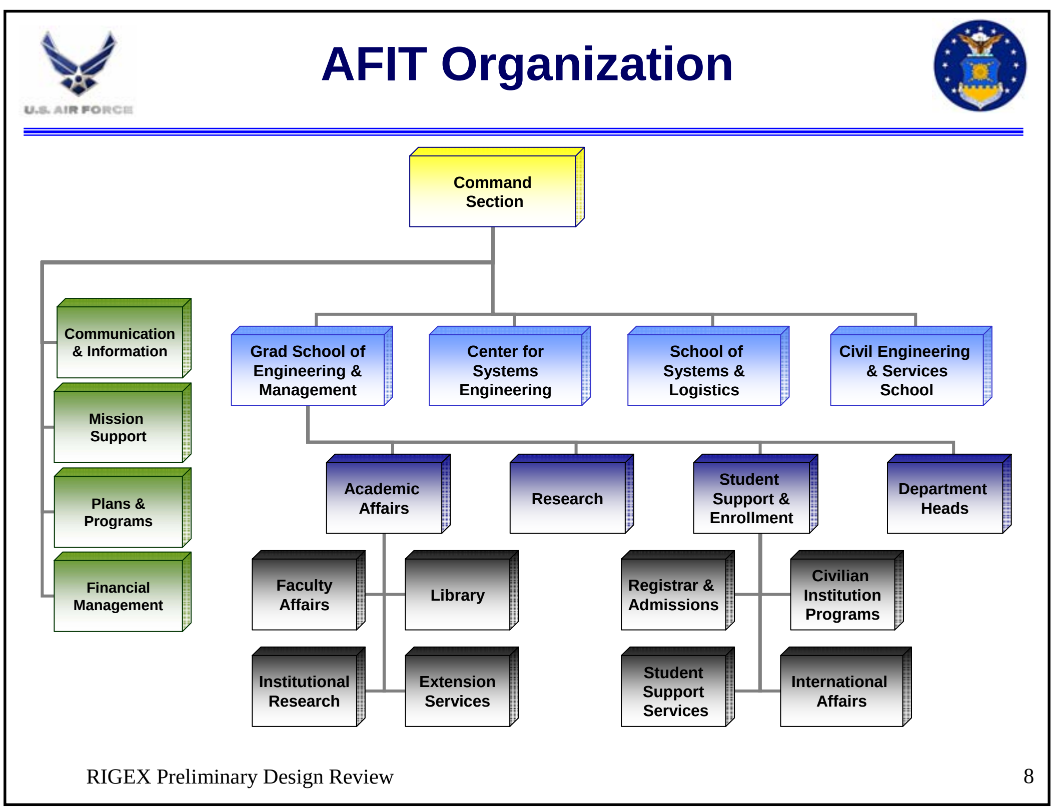
AFIT Organization
U.S. AIR FORCE
Command
Section
Communication
& Information
Mission
Support
Plans &
Programs
Financial
Management
Grad School of
Engineering &
Management
Center for
Systems
Engineering
School of
Systems &
Logistics
Civil Engineering
& Services
School
Academic
Affairs
Research
Student
Support &
Enrollment
Department
Heads
Faculty
Affairs
Library
Registrar &
Admissions
Civilian
Institution
Programs
Institutional
Research
Extension
Services
Student
Support
Services
International
Affairs
RIGEX Preliminary Design Review
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The Graduate School of Engineering and Management

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Col Michael J Caylor, Assoc Dean

Associate Dean for Research
Dr. Heidi Ries

Assistant Dean
Dr. Paul Wolf

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Department of Engineering Physics
Dr. Robert L. Hengehold

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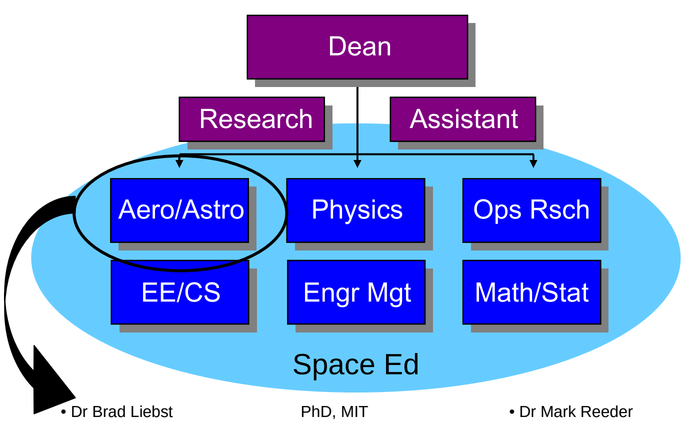
Department of Electrical and Computer Engineering
Lt Col Michael L. Talbert
(Acting)

Department of Operational Sciences
Dr. James T. Moore
(Acting)

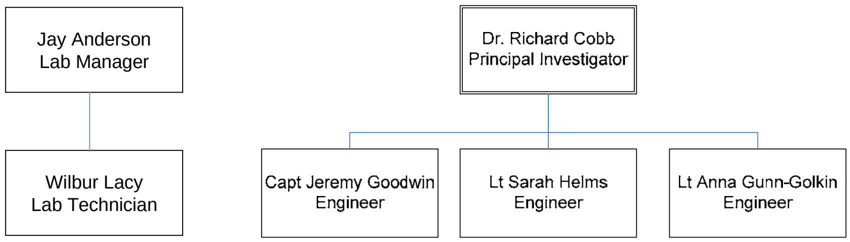
Department of Aeronautics and Astronautics
Dr. Brad Liebst

Graduate School



• Dr Brad Liebst	PhD, MIT	• Dr Mark Reeder	PhD, Ohio State
• Dr R. Anthenien	PhD, UC Berkeley	• Dr A. Palazotto	PhD, New York Univ
• Lt Col M. Hughson	PhD, Miss. State	• Maj R. McMullan	PhD, North Carolina State U
• Dr Milt Franke	PhD, Ohio State	• Dr Curtis Spenny	PhD, Harvard Univ
• Dr Paul King	PhD, Oxford Univ	• Dr William Wiesel	PhD, Harvard Univ
• Dr D. Jacques	PhD, AFIT	• Dr S. Tragesser	PhD, Purdue Univ
• Lt Col R. Canfield	PhD, Virginia Tech	• Lt Col R. Maple	PhD, AFIT
• Dr. Rich Cobb	PhD, AFIT	• Dr S. Mall	PhD, Univ of Washington
• Dr Don Kunz	PhD, Georgia Tech	• Dr M. Ruggles-Wrenn	PhD, RPI

RIGEX Program



Academic Programs

- **MS (18 Months) & PhD (36 Months)**
  - **Aeronautical Engineering**
  - **Astronautical Engineering**
  - **Electrical Engineering**
  - **Computer Engineering**
  - **Nuclear Engineering**
- **MS (18 Months)**
  - **Acquisition Management**
  - **Cost Analysis**
  - **Logistics Management**
  - **Information Resource Management**
  - **Information Systems Management**
  - **Engineering Management**
  - **Environmental Science and Engineering**
  - **Aerospace and Information Operations**

- **Applied Physics**
- **Space Weather**
- **Electro-Optics**
- **Materials Science**
- **Applied Mathematics**
- **Operations Research**

- **Space Operations**
- **Systems Engineering**
- **Operational Analysis**
- **Computer Science**
- **Computer Systems**
- **Masters of Air Mobility at Ft Dix, NJ (12 Months)**

Faculty Profile FY04

- 132 Faculty
  - 87 Refereed Publications
  - 412 Other Publications and Presentations
- 235 M.S. Theses, 16 Ph.D. Dissertations
  - 93% of Technical and 86% of All Sponsored
  - Avg $373k/thesis Cost Avoidance to Sponsor
- $6.2M Reimbursable Research Funding
  - 50% AFRL, 10% NSA, 26% other DoD Research

1.4 RIGEX Objectives

- Goals
  - Provide Air Force students practical hardware experience
  - Provide a military relevant space experiment
- Approach
  - Phased approach using student research
    - Conceptual design through to space flight
    - Combination of Systems Engineering, Astro Engineering, and Electrical Engineering
  - Rely on commercial-off-the-shelf (COTS) hardware
    - Basic experiment bus provides: data handling, payload integration architecture
    - Defines a stable, open system design with simple interfaces

1.5 PDR Reference Documents

- PDR Slide Package
- Mechanical Drawing Package (Draft)
- Parts List
- Electrical Architecture

2. Mission Definition

2.1 Mission Objectives
2.2 Work Breakdown Structure
2.3 Operational Requirements and Restraints

2.1 Mission Objectives

- Collect & store space-based vibration data on three space-rigidized tubes through flight on Space Shuttle
- Recover payload
- Post-process stored data at AFIT
- Compare space-based data with ground-based data
- Share results with industry

Mission Statement:

Verify and validate ground testing of inflation and rigidization methods for inflatable space structures against zero-gravity space environment.

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2.2 Work Breakdown Structure

Rigidizable Inflatable Get-Away-Special Experiment (RIGEX)

Experiment

- *Structure*
  - Mounting Plate
  - Top Plate
  - Ribs
  - Oven Mounting Plate
  - Oven Brackets
  - Oven Door Latches
  - Press Sys Mounting Plates
  - Base Plate
  - Shroud
- *Avionics*
  - Imaging Counter Board
  - Camera Board #1
  - Camera Board #2
  - Camera Board #3
  - Imaging Power Board
  - Imaging PC-104 Computer
  - Filter Board
  - DAQ Counter Board
  - Thermocouple Board
  - Relay Board #1
  - Relay Board #2
  - Data Acquisitions Board
  - DAQ Power Board
  - DAQ PC-104 Computer
  - Avionics Housing Box
- *Harness*
- *Data Handling*
  - Software
- *Inflation*
  - Pressure Cylinder
  - Pressure Transducers
  - Solenoids
  - Diodes
  - Swagelok Connectors
  - Tubing
- *Thermal*
  - Heater Boxes
  - MINCO Patch Heaters
  - Thermostats
  - Thermocouples
- *Test Articles*
  - Sub-Tg Tubes
  - Piezoelastic Patches
  - Accelerometers
  - Pin-Pullers
  - Digital Cameras
  - Lights

Assembly/Integ.

- *GSE*
  - EGSE
  - MGSE
- *Vibrations Lab*
- *Tools*
- *Assembly Procedures*

Testing/Ops

- *Verification Plans*
- *Thermal Model*
- *Structural Model*
- *Test Reports*
  - Student Theses
  - Intern Papers
- *Ops Procedures*

Systems Engineering

- *SE Reviews*
  - PDR
  - CDR
  - FRR
  - Phase 0/I SR
  - Phase II SR
  - Phase III SR
- *Design Documents*
  - DD Form 1721
  - MoA
  - PRD
  - PDR Slide Package
  - CDR Slide Package
  - Drawing Package
  - Parts/Materials List
  - Mass Properties Report
  - Harness Definition
  - Safety Data Package
  - SVP
  - FCP
  - MSVP
- *CAPE Integration*

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2.3 Operational Requirements and Restraints

- RIGEX shall be launched and returned on the Space Shuttle
  - Value of Flight Hardware Retrieval: Absolutely necessary to retrieve this experiment – all data is collected internally (no telemetry)
- RIGEX has no specific orbital, pointing, stabilization, or telemetry requirements
- RIGEX requires approximately 4 hours of operational time while in orbit
- *Physical Requirements:* RIGEX shall be fully contained within the CAPE experiment envelope
  - RIGEX Dimensions:
    - Diameter: 20.5” (52.07cm)
    - Height: 30” (cm) – 28.5” from CAPE mounting plane to cantilevered end
  - Required Volume: 9242 cubic inches (151.5*10^3 cc)
  - Complete RIGEX experiment must have a natural frequency greater than 50 Hz
- *Power Requirements*
  - Power Relay K1(Experiment Operation): 24-30 VDC, 7 Amps
  - Power Relay K2 (Environmental heaters): 18-30 VDC, TBD Amps
- *Vibration Restraints*
  - Required: None
  - Desired: On-orbit burn & astronaut activity data/timeline for post processing

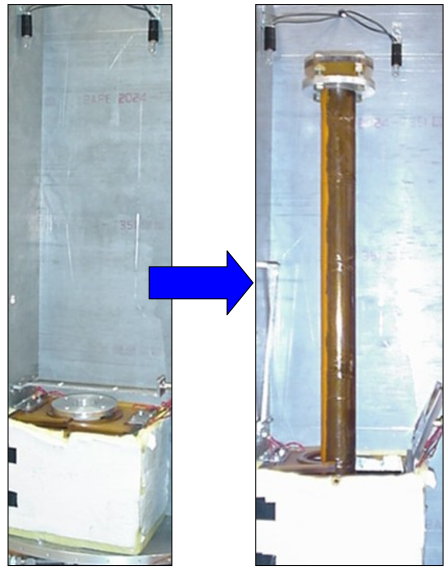
3. Experiment Overview

3.1 Concept
3.2 Key Components
3.3 Justification
3.4 Instrumentation

3.1 Concept

- Objective: Produce and fly experiment to collect data on inflatable rigidizable structures in the space environment

- Concept:
  - Launch on Shuttle in self-contained *Container for All Payload Ejections* (CAPE) canister
  - Heat and inflate three individual tubes
  - Cool tubes to make them structurally stiff
  - Vibrate stiffened tubes using piezoelectric patches
  - Collect data on inflation and vibration with environmental, video, and vibration sensors
  - Analyze tubes on return to determine effects of deployment on composite material



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3.1 Concept

Comparison to Mechanical Structure

24-foot long truss, sub-Tg composite, weight: 9 lbs

RIGEX Tube Properties

Property Description	Value	Units
Tube Diameter	1.5	inches
Tube Material Thickness	15	mils
Young's Modulus	$9.5E\times10^{6}$	lbf/in*sec^2
Moment of Inertia	19.881×10^{-3}	in^4
Material Density	53.957	lbf/ft^3

- **Advantages over Comparable Mechanical Systems:**
  - Weight Savings
  - Volume Savings
  - Engineering Cost Savings
  - Production Cost Savings

= **Substantial $$$$$ Saved**

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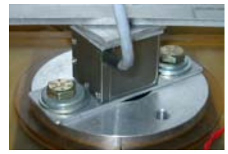
3.2 Key Components

- **Sub-Tg Inflatable Tubes**
  - Kevlar fibers with polyurethane-based resin
  - 125°C glass-transition temperature (Tg)
  - Tubes are rigid below and pliable above 125ºC
  - Excited with piezoelectric patch for characterization
  - Tube Caps made of machined 6061 Aluminum
    - Base Cap = 74.02 g
    - Tip Flange = 74.6 g
    - Tube Material ≈ 94 g
- **Piezoelectric Patch**
  - First Flight – will test performance in space
  - Developed by NASA-Langley
  - Piezoelectric actuators are bonded near tube's cantilevered end
- **Accelerometer (Accel.)**
  - Bolted onto tube's free end

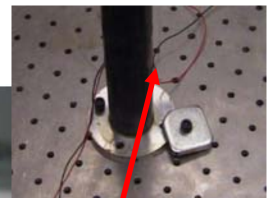


Accel. mounted here

Inflated/Rigidized Tube

Folded Tubes

Piezoelectric Patch



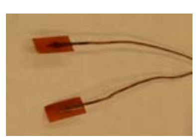
PZT Actuator

3.2 Key Components

Initial RIGEX Structure (will be re-fabricated)

PC-104 Computer Boards

Computer Housing

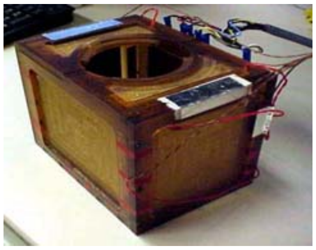


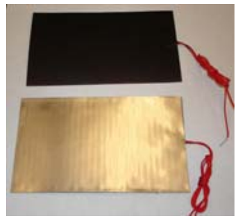
Thermocouples

Power Relay

Transformer

3.2 Key Components


Oven


MINCO Heaters


Solenoid


Pressure Cylinder


Shape Memory Pin-Puller


Digital Camera

3.3 Justification

- **Military Relevancy**
  - RIGEX data is a step toward making inflatable space structures more viable
    - Large aperture sensors, large space structures, solar sails, solar power collectors, space telescopes, etc.
- **Need For Space Test**
  - Correlate behavior of inflatable rigidizable structures in the space environment and on the ground
    - Record deployment characteristics
      - Previous experiments have had unexpected deployment behavior
      - Light-weight and flexibility of materials makes zero-gravity testing essential
    - Determine modal characteristics of deployed tubes to compare with ground test results
      - Modal characteristics crucial for space antennas and other highly sensitive platforms
    - Run a materials analysis on tubes when returned
      - Analyze fiber breakage and delamination of the composite structure
- **Comparison to Alternatives**
  - Lower cost, lighter weight, & smaller packaging
  - Risk-mitigation experiment for future inflatable/rigidizable missions

3.4 Instrumentation

- Accelerometers
  - One per tube, mounted on free end
  - Triaxial, +/- 12 VDC
  - Post-processing of accelerometer data reveals tube natural frequencies
- Thermocouples
  - Two per tube, mounted on determined "coldest" points of folded tube
- Piezoelectric Actuators
  - Two per tube, mounted at base of tube opposite of each other
  - Two actuators work together to create vibration of tube
- Digital Cameras
  - One per tube
  - Still images used to:
    - Record orientation during inflation
    - Measure height / tilt angle at end of inflation
- Pressure Transducers (absolute)
  - Two per experiment bay
  - First measures cylinder pressure
  - Second records tube pressure
- Thermostats
  - One per environmental heater, location TBD

4. System Configuration

4.1 Physical Configuration

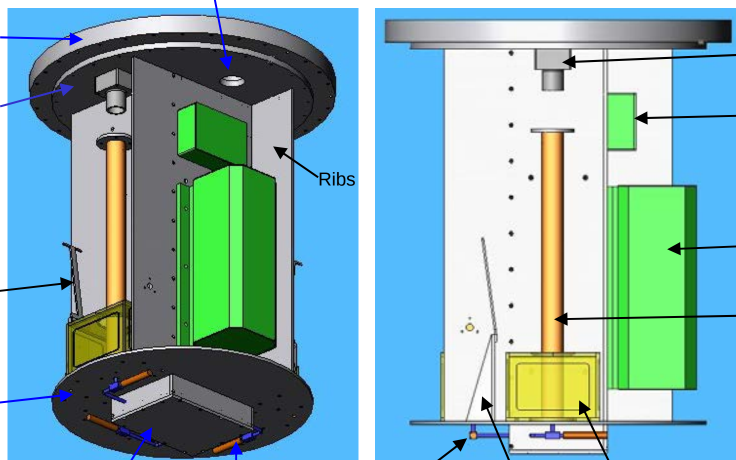
4.2 Coordinate System

4.3 Equipment List

4.4 Mass Properties

4.5 Configuration Issues

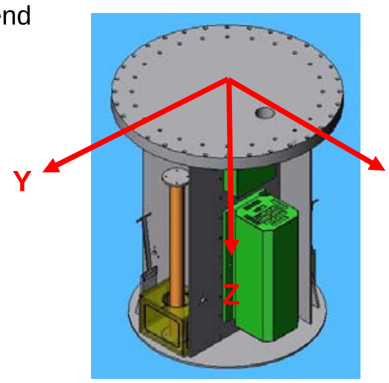
4.1 Physical Configuration



4.2 Coordinate System

- “Top” end of experiment is cantilevered
- “Bottom” end of experiment is free

- Origin is at center of structure’s cantilevered end
  - X: Positive towards computer
  - Z: Positive towards structure’s free end
  - Y: Completes right-hand rule



4.3 Equipment List

- Detailed Parts List available in PDR Reference Documents package
- Materials List started, some initial information available in Parts List
- Key Components
  - Structure
  - Fasteners (TBD)
    - Bolts
    - Washers
    - Nuts
  - Bumper / Snubber (4)
  - PC-104 Computer Boards
    - Processor (2)
    - A/D
    - Power Supply (2)
    - Relay (2)
    - Timing/Counter (2)
    - Thermocouple
    - Camera (3)
    - Filter Board
  - Computer Housing
  - Fuse / Electrical Box
  - Power Relay (3)
  - Wiring
  - Connectors (TBD)
  - Sub-Tg Tube (3)
  - Accelerometer (3)
  - Thermocouple (6; 2 per tube)
  - Piezoelectric Actuator (6; 2 per tube)
  - Transformer (3)
  - Pin Puller (3)
  - Oven (3)
  - Oven Door Latch (3)
  - Heaters (27 total)
    - Oven (24; 8 per oven)
    - Environmental (TBD; placed on outside of computer housing)
  - Thermostat (1 per environmental heater)
  - Pressure Cylinder (3)
  - Pressure Transducer (6)
  - Solenoid (3)
  - Diode (3)
  - Tubing
  - Pressure Fittings and Adaptors
  - Digital Camera (3)
  - LED Light (6; 2 per experiment bay)

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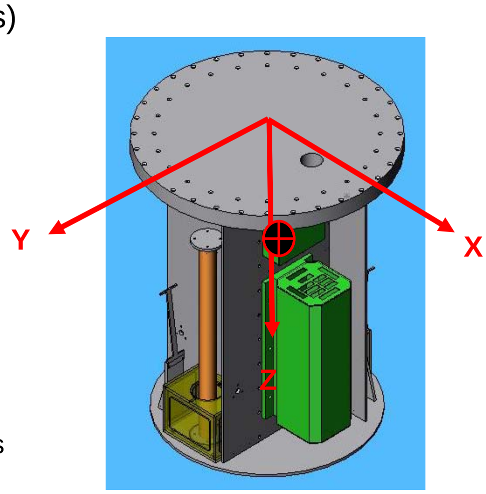
4.4 Mass Properties

- Total Mass: ≈79.8 kg (175.9 lbs)
- Center of gravity:
  - x = 0.7 in from centerline
  - y = 0.1 in from centerline
  - z = 7.9 in from CAPE connection plane
  - Detailed analysis of individual component COG available
- Assumptions
  - Uniform density of components
  - Forecast parts with TBD locations will be added and slight structure changes will be made



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4.4 Mass Properties

Component	Quantity	Mass (g)	Total Mass (g)
Fasteners	TBD	TBD	0
Bumpers	4	TBD	0
PC-104 Computer Boards	1	2500	2500
Computer Housing	1	2870	2870
Power Relay	3	113.8	341.4
Wiring	TBD	TBD	0
Connectors	TBD	TBD	0
Sub-Tg Tube	3	242.2	726.6
Accelerometer	3	38	114
Transformer	3	172	516
Pin Puller	3	44.3	132.9
Oven	3	570	1710
Environmental Heaters	3	3.9	11.7
Thermostats	3	TBD	0
Pressure Vessel	3	1216	3648
Pressure Transducer	6	TBD	0

Component	Quantity	Mass (g)	Total Mass (g)
Solenoid	3	102.3	306.9
Digital Camera	3	230	690
Lights	6	TBD	0
Mounting Plate	1	29478.46	29478.46
Shroud	1	11337.9	11337.9
Press Sys Mounting Plates	2	453.5	907
Structure	1	24489.8	24489.8
		Total:	**79.8 kg**
			175.9 lbs

- Working copy of RIGEX mass calculations
  - Yellow indicates areas where mass will be added, TBD

4.5 Configuration Issues

- CAPE to RIGEX connector
  - Size, type
- Bumpers / Snubbers
  - Size, type, location
  - Anticipate they will provide significant balance to eliminate the need for a "bottom plate"
- Location for the following components TBD:
  - Environmental Heaters
  - Thermostats
- Wiring holes not fully integrated into Drawing Package
- Routing of all wiring within RIGEX structure is TBD

5. Mechanical Subsystem

5.1 System Specifications
5.2 Mechanical Design Status
5.3 Mechanical Ground Support Equipment
5.4 Open Issues

5.1 System Specifications

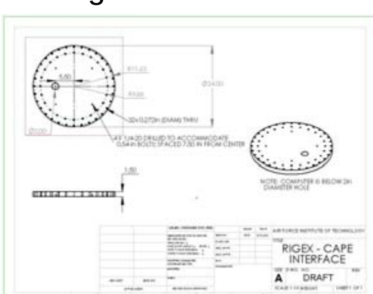
- The RIGEX Structure shall physically support all subsystem equipment.
- RIGEX Structure shall withstand 10 g's in three directions with a factor of safety = 2.0
- RIGEX Structure first natural frequency shall be greater than 50 Hz
- Operational Requirements and Constraints
  - RIGEX Structure shall be capable of mechanical interface with MGSE, shipping containers and CAPE.

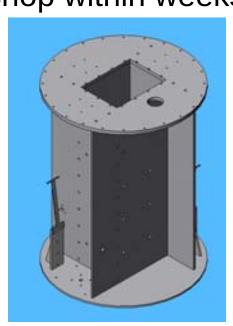
5.1 System Specifications

- Configuration
  - RIGEX consists of a cylindrical structure divided into four experiment bays surrounding an inner pressure system bay. Three Sub-Tg tube experiments are housed in the experiment bays; the fourth bay houses the RIGEX computer.
  - *Structure*
    - Material: Aluminum 2024-T351 or 6061 Plate (TBD based upon machine shop availability)
    - RIGEX to CAPE Mounting Plate: 1.5” Thick
    - Top Plate: 0.5” Thick
    - All Remaining Plates: 0.25” Thick
    - Density: 0.1 lb/in^3
  - *Shroud*
    - Material: Aluminum 2024-T3 or 6061 Sheet (TBD based upon machine shop availability)
    - Density: 0.1 lb/in^3
    - 0.125” Thick -- TBD

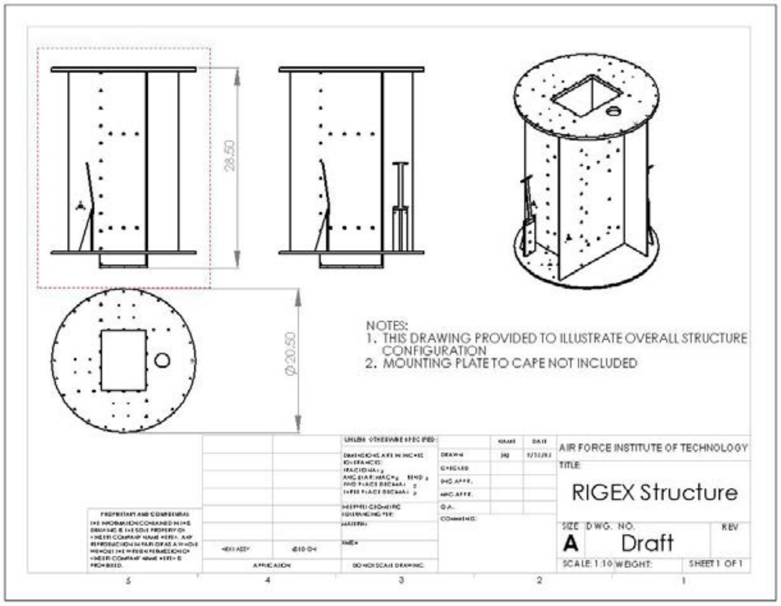
5.2 Mechanical Design Status

- General design is complete
  - With exception of the Configuration Issues from Section 4
- Parts List ~ 70%
- Drawing Package Status
  - Manufacturing Drawings ~ 90%
  - Assembly Drawings ~ 85%
- Drawings to be submitted to machine shop within weeks





5.2 Mechanical Design Status



5.2 Mechanical Design Status

- Shape Memory Alloy (SMA) actuated Pin-Puller manufactured by TiNi Aerospace, Inc.
  - Developed under contract from NASA Lewis Research Center - Qualification and Acceptance tested for flight qualification
  - Functional Life > 100 cycles

Shape Memory Pin-Puller

5.3 Mechanical GSE

- GSE is required for shipping/moving RIGEX payload at processing facility
- Options available at Keal (www.kealcase.com)

Pull-Over Lid

Clam Shell

- Lift points (4) built into top plate for mating with CAPE lifting sling bolts

5.4 Open Issues

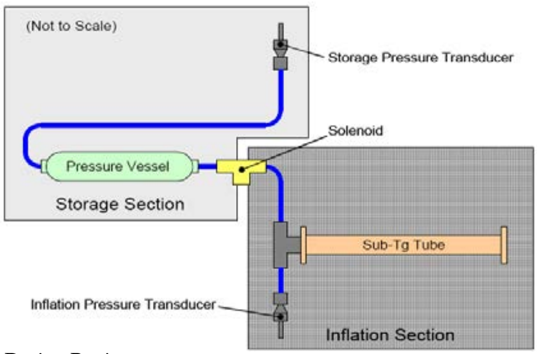
- Completion of Mechanical Drawings for submission to machine shop
  - Need to add all holes need for electrical wire routing
  - Placement of all TBD parts
- Shroud
  - 1/8 inch 6061 aluminum currently
  - Waiting on conclusion of punch-through analysis to solidify thickness
    - Shroud thickness will be designed according to SSP 52005 Rev C
- Fasteners
  - Will use NAS fasteners with thread patch and pre-load as the two required locking devices
  - Need to update parts list to include details of all fasteners and then order
  - Fastener integrity program will be implemented once hardware is received

6. Inflation Subsystem

6.1 System Specifications
6.2 Block Diagram
6.3 Physical Configuration
6.4 Status
6.5 Open Issues

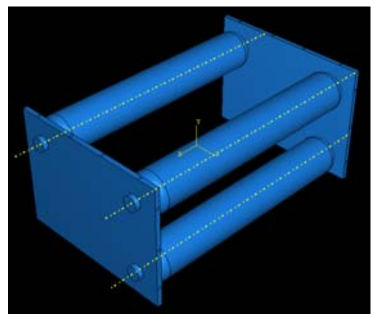
6.1 System Specifications

- RIGEX pressure system shall:
  - Provide inflation pressure between 4 and 10 PSIA to each Sub-Tg tube over their inflation and cooling period durations
  - Store nitrogen gas for inflation at 14.7 PSIA
  - Include sensors to feed pressurization information back to the computer
  - Fit within the RIGEX inner bay
- Pressure system shall meet all Shuttle safety requirements and be designed such that it maximizes reliability and redundancy.



6.2 Physical Configuration

- Definition of a “sealed container” according to NASA-STD-5003 paragraph 3.39:
  - “Any single, independent (not part of a pressure system) container, component, or housing that is sealed to maintain an internal non-hazardous environment and that has a stored energy of less than 14,240 foot-pounds (19,310 Joules) and an internal pressure of less than 100 psia (689.5 kPa).”
  - RIGEX pressure system consists of a cylinders, tubing, and components pressurized to 14.7 psia with nitrogen gas
    - RIGEX pressure system is considered a “sealed container”
    - RIGEX pressure system is also compliant with the four requirements for sealed containers listed NASA-STD-5003 paragraph 4.2.2.4.3.2a
- Pressure system key components:
  - Pressure Cylinders (3)
  - Solenoids (3)
  - Diodes (3)
  - Pressure Transducers
    - Storage Sensors (3)
    - Tube Inflation Sensors (3)
  - ¼” Tubing
  - Pressure fittings, connectors, and adaptors
  - Nitrogen gas



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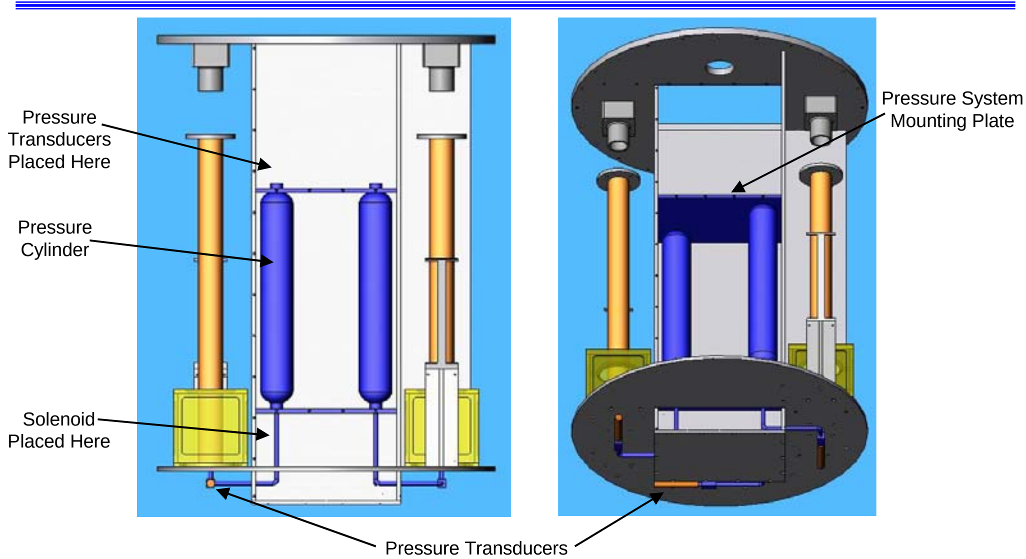
6.2 Physical Configuration



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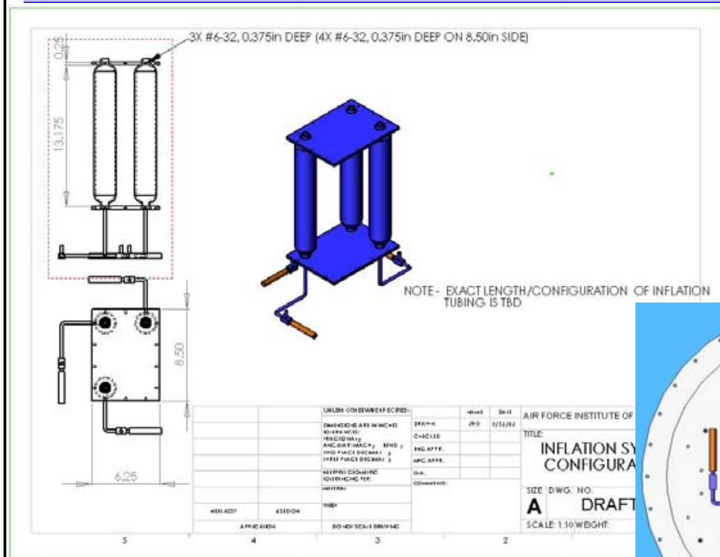
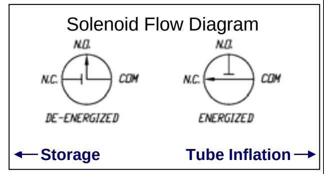
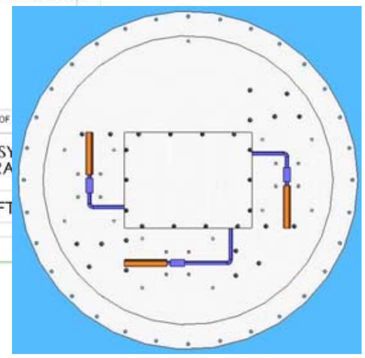
6.2 Physical Configuration







6.3 Block Diagram

located in experiment bay

L'Guarde Sub-Tg tube
20" long, five folds in stored configuration
Transition temperature: 125º C

Inflation Pressure Transducer
Taber Industries bonded foil
sensing technology pressure transducer
Part Number: M2911C150AEGAAA1

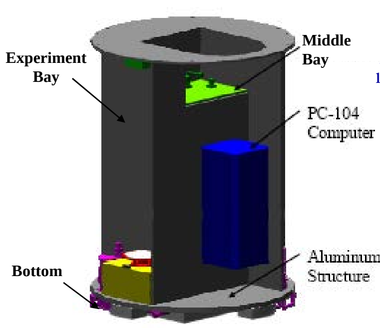
Swagelok Pipe Tee

¼" OD pipe, Salem Tube Inc.
≈ 10" length (two 90º bends)
Passes through ½" aluminum structure wall via mil std grommet
Part Number: HT#OPY937

Solenoid Valve, Parker Instrumentation
VAC – 100 psig, DC 24 V
Part Number: 009-0143-900

located in "bottom" of canister

located in middle bay



Swagelok Pressure Cylinder
1800 psig, 500 cm^3 volume, 2.6 lbs (1.2 kg)
2" diameter, 13.8" length, 0.093" wall thickness
316L Stainless Steel / Part Number: 316L-HDF4-500

Cylinder Specs:
DOT 3E 1800 TC SU6158 124 / Hydrostatically proof tested at 3050 psig

Storage Pressure Transducer
Taber Industries bonded foil
sensing technology pressure transducer
Part Number: M2911C150AEGAAA1

6.4 Status

- Pressure cylinders, solenoids, diodes, tubing, wiring, and all pressure fitting/connectors/adaptors in house
- Plates designed to secure pressure system to structure
- Pressure transducers ordered from Taber Industries
  - Long lead time, waiting arrival
- Pressure system mounting plate order to be placed at machine shop with rest of structure

6.5 Open Issues

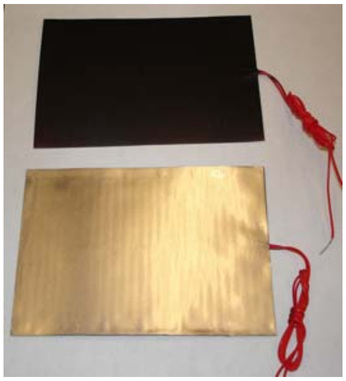
- Fill/purge of cylinders TBD
  - Use air for all testing, purge with nitrogen for flight
- Grommet material not approved for use
  - Currently looking at ordering sheets of Viton material to use between the following interfaces:
    - Pressure Cylinder – Pressure System Mounting Plates (6 locations)
    - Tubing – Through Hole of Ribs (3 locations)

7. Thermal Subsystem

7.1 System Specifications
7.2 Status
7.3 Open Issues

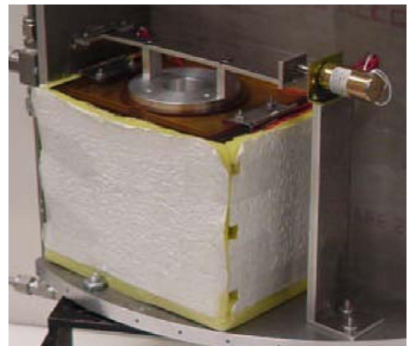
7.1 System Specifications

- **RIGEX thermal system purpose is two-fold:**
  - RIGEX thermal system will provide adequate heat to each RIGEX oven in order to transition the enclosed Sub-Tg tube over 125°C
  - RIGEX thermal system will provide environmental control for all mission essential hardware that cannot withstand low temperatures of the space/CAPE environment



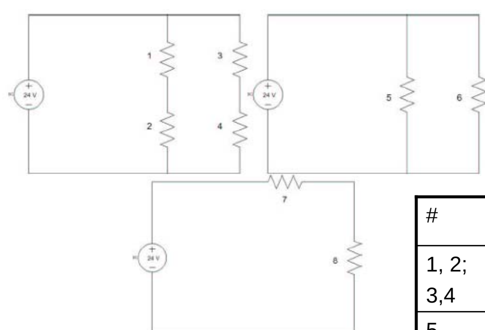
7.1 System Specifications

- Ovens
  - Material: 0.25” thick Ultem 1000 PEI Polyetherimide, milled down to 0.125”
  - Foam insulation taped (Kapton) to outside of oven (not shown)
  - Inside lined with aluminum foil to increase reflectivity of heater radiation
- Resistive Heaters
  - Adhesive-backed MINCO heaters
  - Painted flat black to increase emissivity
- Thermostatically-Controlled Environmental Heaters (TBD)
  - MINCO heaters, thermostats programmed by MINCO
  - Ensure computer temperature is above 0ºC
  - Connected to Shuttle’s K2 relay



7.2 Status

- Oven design is complete
- Resistive heater circuit design is complete (3 circuits per tube):



- Above parts are in house

#	Location	Resistance
1, 2; 3,4	Top; Bottom	9Ω
5 6	Front Back	21 Ω
7 8	Left Right	10.2 Ω

7.3 Open Issues

- Environmental heaters/circuits need to be determined/ordered
- Current draw of environmental heaters needs to be determined
- Concern for oven heaters warping the oven structure with extended usage

8. Electrical Power Subsystem

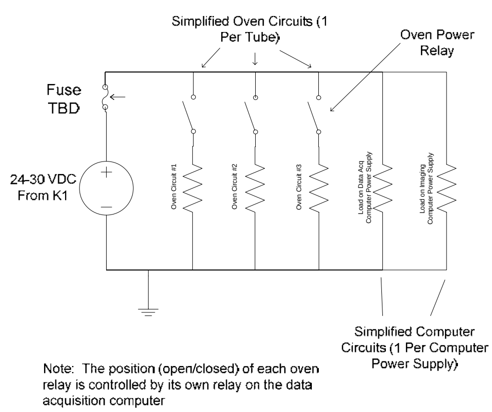
8.1 System Specifications
8.2 Status
8.3 Open Issues

8.1 System Specifications

- Shuttle-supplied Power: 24-30VDC, 7A (Shuttle K1 Relay)
  - Sustained voltage above 31 VDC may damage power supply
  - Outputs: +/- 5 VDC, +/- 12 VDC
- Environmental Heater Power: 18-30 VDC, TBD A (Shuttle K2 Relay)
- Harness
  - Internal Computer Wiring: Teflon High Performance 50-Conductor 0.050 pitch Ribbon Cable (SCSI1FEP-100, www.mycableshop.com)
  - Wiring connecting pressure transducers: MIL-W-22759/4
  - Wiring connecting all other components: MIL-W-22759/11
- K1 Switch Positions
  - S13 Up = +18V when computer is running, 0V when computer is off
  - S13 Down = +18V when computer is off, 0V when computer is on
- K2 Switch Positions
  - S15 = +18V when environmental heaters need power (non-latching switch)

8.1 System Specs (Cont)

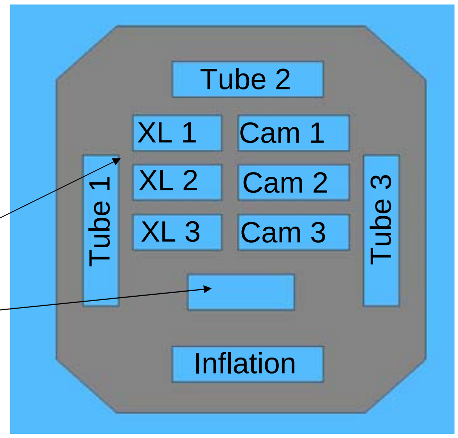
- Items connected directly to 24 VDC supply from K1(after fuse):
  - Computer power supplies (2)
  - Resistive heater power relays (3)



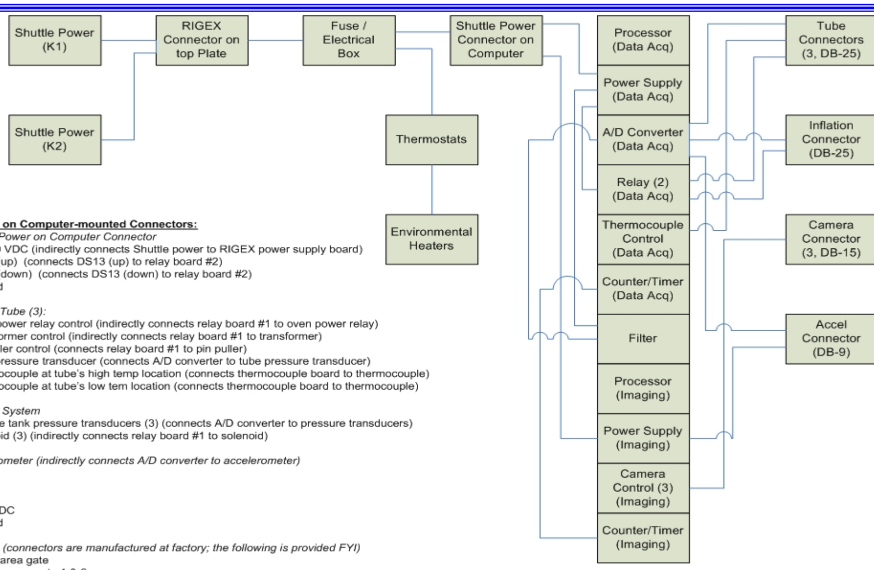
8.1 Computer Connector Plate

- Connectors on Top of Computer
  - 25-pin connector (4)
    - 1 per tube; 1 for inflation system
  - 9-pin connector (3)
    - 1 per accelerometer
  - 15-pin connector (3)
    - 1 per camera
  - Shuttle Power connections
    - TBD

Notes:
- XL = accelerometer
- Min sep distance: 0.125”
- Allowable space for connection to Shuttle power from fuse box (can be enlarged if necessary)



Electrical Architecture



Signals on Computer-mounted Connectors:

Shuttle Power on Computer Connector
+24-30 VDC (indirectly connects Shuttle power to RIGEX power supply board)
DS13 (up) (connects DS13 (up) to relay board #2)
DS13 (down) (connects DS13 (down) to relay board #2)
Ground

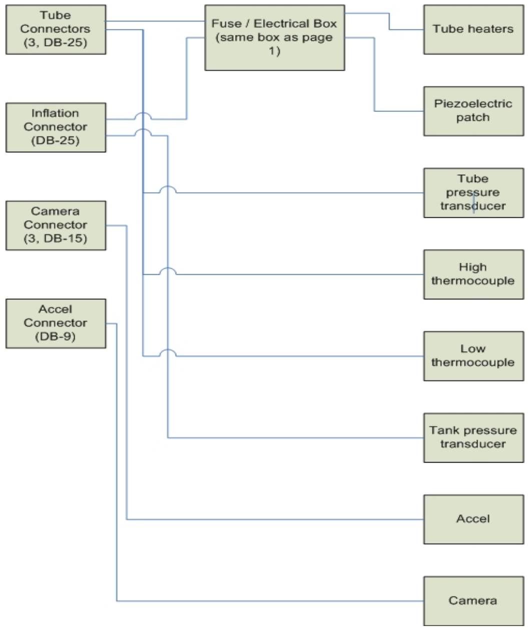
Sub-Tg Tube (3):
Oven power relay control (indirectly connects relay board #1 to oven power relay)
Transformer control (indirectly connects relay board #1 to transformer)
Pin puller control (connects relay board #1 to pin puller)
Tube pressure transducer (connects A/D converter to tube pressure transducer)
Thermocouple at tube’s high temp location (connects thermocouple board to thermocouple)
Thermocouple at tube’s low tem location (connects thermocouple board to thermocouple)

Inflation System
Storage tank pressure transducers (3) (connects A/D converter to pressure transducers)
Solenoid (3) (indirectly connects relay board #1 to solenoid)

Accelerometer (indirectly connects A/D converter to accelerometer)
Axis 1
Axis 2
Axis 3
+ 12 VDC
Ground

Camera (connectors are manufactured at factory; the following is provided FYI)
Image area gate
Storage area gate 1 & 2
Anti-blooming gate
Combined serial register gates
Analog video signal
+ 11 VDC (regulated)
Ground

Electrical Architecture



Components in Fuse/Electrical Box
Fuses (TBD, fuse shuttle AUG with RIGEX AUG)
Oven power relay (connected to Tube connector)
Transformer (connected to Tube connector)
Diode (connected to Inflation connector; connects computer to solenoid; prevents voltage return from shutting computer down when solenoid relay is closed)

8.2 Status

- Wiring harness design is complete
  - Test harness is built and being tested
  - Accel and Camera connectors were predetermined by manufacturers

Camera Connector

Pin	
1	Image area gate
2	Storage area gate #1
3	Storage area gate #2
4	Anti-blooming gate
5	Combined serial register gate
6	---
7	---
8	---
9	Analog video signal
10	Combined transfer/transfer multiplex gate
11	Ground
12	+11 VDC (regulated)
13	Ground
14	---
15	---

Accel Connector

Pin	
1	Data - Axis 1
2	---
3	Data - Axis 1
4	---
5	Data - Axis 1
6	---
7	---
8	voltage input (+5V)
9	ground

Tube Connector

Pin	Description
1	+ control input for oven power relay
2	- control input for oven power relay
3	---
4	---
5	Transformer (solid lead)
6	Transformer (striped lead)
7	---
8	---
9	Pin puller (white lead)
10	Pin puller (black lead)
11	---
12	---
13	---
14	---
15	---
16	---
17	Tube pressure sensor (green wire)
18	Tube pressure sensor (white wire)
19	Tube pressure sensor (red wire)
20	Tube pressure sensor (black wire)
21	High Thermocouple (brown wire)
22	High Thermocouple (red wire)
23	Low Thermocouple (brown wire)
24	Low Thermocouple (red wire)
25	---

Pressure Connector

1	Tank #1 pressure sensor (green wire)
2	Tank #2 pressure sensor (green wire)
3	Tank #3 pressure sensor (green wire)
4	Tank #1 pressure sensor (white wire)
5	Tank #2 pressure sensor (white wire)
6	Tank #3 pressure sensor (white wire)
7	Tank #1 pressure sensor (red wire)
8	Tank #2 pressure sensor (red wire)
9	Tank #3 pressure sensor (red wire)
10	Tank #1 pressure sensor (black wire)
11	Tank #2 pressure sensor (black wire)
12	Tank #3 pressure sensor (black wire)
13	---
14	---
15	---
16	---
17	---
18	---
19	Solenoid #1 positive lead
20	Solenoid #1 negative lead
21	Solenoid #2 positive lead
22	Solenoid #2 negative lead
23	Solenoid #3 positive lead
24	Solenoid #3 negative lead
25	---

8.3 Open Issues

- Exact routing of harness needs to be determined
- Flight harness needs to be built
- Flight connectors need to be identified/purchased
- Connections through structure compartments needs to be determined
- Circuits for S13 switches need to be designed; software needs to be developed
- Second Relay board added to schematics recently
  - Need to determine if it is necessary or not before ordering

9. Command & Data Handling / Flight Software

9.1 System Specifications
9.2 Status
9.3 Open Issues

9.1 System Specifications

- Software is written in C++
  - Operation is completely autonomous
  - Post-processing is performed via MATLAB code
  - Code can be made available upon request
- Code Overview
  - Initialize computer boards – send at least +18V to DS13(up), 0V to DS13(down)
  - Check failsafe file – if experiment has previously started, go to last saved position
  - Perform self test
  - Initialize heating process for oven/tube #1
    - Computer records two thermocouple readings during heating process
    - Smallest reading of two thermocouples must be 125ºC for 10 iterations before inflation begins
    - Mark failsafe file

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9.1 System Specs (cont)

- Engage pin-puller
  - Release latch that holds oven doors closed during launch
- Inflate tube
  - Initialize digital camera to take images of tube during inflation
  - Open solenoid
  - Use pressure transducer to record tube pressure during inflation
  - Close solenoid
  - Halt imaging
  - Wait for tube to cool (software pauses using a “while” counting loop)
  - Mark failsafe file
- Take one image
  - Capture tube orientation after inflation (height/tilt angle)
  - Mark failsafe file

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9.1 System Specs (cont)

- Excite tube
  - D/A Convert 0-1000 Hz chirp signal (signal is then filtered using 8^{th}-order Butterworth filter)
  - Send signal to transformer; transformer boosts signal to piezo's by 50x
  - Record 3 signals from triaxial accelerometer through filter and A/D converter (post-processing done on ground)
  - Mark failsafe file
- Take one image
  - Capture tube orientation after excitation (height/tilt angle)
  - Mark failsafe file
- Power all tube 1 components off
  - Note: lights for all tubes are on same relay, so all will be on at same time
- Initialize heating process for oven/tube #2
  - Process repeats itself for tube #2 & 3

9.2 Status

- End-to-end run-throughs have been completed successfully prior to test harness integration
  - Verified all computer boards/components work together
    - Note: Accel type may need to be re-evaluated -- see next slide
- Step-by-step runs are in process now – transition between students has caused complications here but no major issues are anticipated
  - Heating process: complete
  - Pin puller actuation: complete
  - Inflation process: incomplete--haven't attached inflation system
  - Solenoid actuation: complete
  - Excitation process: complete
  - Imaging process: incomplete--see next slide

9.3 Open Issues

- Accel data is very noisy -- may need to re-evaluate type used
  - Currently looking at filter
- Data acquisition and imaging computer counter boards are not communicating
  - Data acquisition counter board's most-significant-bit pin stopped working
  - New boards (same model #) have been purchased
  - Currently troubleshooting malfunction
  - This prevents imaging process from being completed
- Self test needs to be written
- Code for DS13 needs to be written
- Current relay board is full (no open relays exist)
  - Additional relay board will need to be purchased for DS13 interface
- Complete run through with test harness needs to be completed

10. Test and Evaluation

10.1 RIGEX History
10.2 Future Tests
10.3 Status
10.3 Open Issues

10.1 RIGEX History

- 2001 John DiSebastian
  - RIGEX preliminary design, top level Systems Engineering
- 2002 Thomas Single
  - Experimental vibration analysis of a single Sub-Tg Tube
  - Created a baseline for beam characterization on the ground
    - First step in RIGEX primary goal - correlate ground test data with space flight results to increase the use of inflatable, rigidizable structures in space applications
- 2003 Thomas Philley
  - End-to-End inflation and rigidization of a single Sub-Tg Tube
  - Continued Sub-Tg Tube vibration analysis
    - Natural frequency and damping ratio results with multiple different boundary conditions
  - **Sub-Tg Tube (Accelerometer data)**
    - **1st Natural Frequency (Bending): 59.7 Hz**
    - **2nd Natural Frequency (Bending): 660 Hz**
- 2004 David Moody
  - Initial design of the Data Acquisition and Imaging computer system

10.1 RIGEX History

- 2004 Raymond Holstein
  - Structural analysis with a finite element analysis approach compared to ping testing of physical structure
  - **Fully massed structure modes (According to results of FEM)**
    - **1st Natural Frequency: 54 Hz**
    - **2nd Natural Frequency: 63 Hz**
  - **Ping testing results (Structure Only)**
    - **1st Natural Frequency: 94 Hz**
- 2004 Steven Lindemuth
  - Characterization of heating and inflation process
    - Determined slowest heating location of tube to be fold #2
- 2005 Chad Moeller
  - Handled payload envelope change from GAS to CAPE canister
    - Instigated pressure system redesign
  - Determined cooling profile of Sub-Tg Tubes

10.2 Future Tests

- Part Testing
  - End-End avionics/software test
    - Use re-folded tubes with flight software
    - Verify heating/inflation/excitation/imaging/data recording
    - Verify computer connectivity to all components
  - Vibration testing of heater box + Tube
    - Structural verification of heater box
    - Impact of launch environment on folded Sub-Tg Tube
  - Pressure system leak testing
    - Verify integration competency
    - Determine if further leak tests are necessary
- Fully Assembled RIGEX Testing
  - Self Test / Interface Verification Test (electrical)
  - 3-Tube Deployment Test, Ambient
    - Verify full experiment integration
    - Use re-folded tubes
  - Structural vibration test
    - Combination of structural frequency and structural verification test
    - Complete Static Loads, Sine Burst, Sine Sweep, and Random Vibration tests as directed by STP
    - Verify all RIGEX components survived vibration testing using Self Test

10.2 Future Tests

- Fully Assembled RIGEX Testing, continued
  - Thermal Vacuum Test
    - Verify operation of all components at +/-60ºC (or alternate profile determined by STP)
    - Complete 3-Tube deployment test or make use Self Test if determined applicable
    - Facility/test dates TBD
  - Electromagnetic Tests
    - EMI, EMC, radiated/conducted emissions, radiated/conducted susceptibility
    - Use Self Test to evaluate RIGEX electromagnetic activity/susceptibility
    - Locations and methods TBD
  - CAPE to RIGEX Interface Verification Test (physical)
- STP Controlled Tests
  - Fastener Destructive Testing
  - Wire Testing
    - Flight wire is in house - test can be done at any time

10.3 Status

- Engineering Model structure is built
  - Based on previous design -- flight model requires minor updates
    - Increase overall diameter to 20.5”
    - Add bumpers/snubbers to bottom of experiment under inflation system tubing
    - Eliminate computer access port in Top Plate and increase plate thickness
    - Add Mounting Plate
    - Incorporate all holes for parts with TBD locations and wire routing
  - Used for fit checks
- Computer internal test harness is built and being tested
  - Already has identified form/fit issues
  - Flight harness will be made with qualified wiring and connectors after full layout is solidified
- Fabrication of Flight Model structure coincides with individual part testing

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10.4 Open Issues

- Test dates/facilities need to be determined
  - Especially electromagnetic and thermal testing
  - As risk reduction, need to determine method for electromagnetic testing in near future
- Test plans need to be written
- Acceptable CAPE profiles for structural verification needed:
  - Static Loads Test
  - Sine Burst Test
  - Sine Sweep Test
  - Random Vibration Test
  - Thermal Test

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11. Mission Operations

11.1 Mission Ops Concept
11.2 Ground Ops
11.2 Open Issues

11.1 Mission Ops Concept

- Operations are completely autonomous once power is applied
- Apply power to environmental heaters
- Apply power to experiment
- Mission timeline:

Computer turn on (CTO); DS13(up) gets +18V	CTO
Self-test begins	CTO + 180 s
Self-test ends; 5-min wait period for computer shutdown starts	CTO + ~ 380s
Oven #1 heating initialized	CTO + 680 s
Tube #1 deployment initialized	CTO + 4280 s
Tube #1 is fully deployed/begins cooling	CTO + 4300 s
Tube #1 is cooled to vent temp/vents	CTO + 4900 s
Tube #1 actuation	CTO + 4910 s
Tube #1 complete; Begin heating Tube #2	CTO + 4940 s
Tube #2 deployment initialized	CTO + 8540 s
Tube #2 is fully deployed/begins cooling	CTO + 8560 s
Tube #2 is cooled to vent temp/vents	CTO + 9160 s
Tube #2 actuation	CTO + 9170 s
Tube #2 complete; Begin heating Tube #3	CTO + 9200 s
Tube #3 deployment initialized	CTO + 12800 s
Tube #3 is fully deployed/begins cooling	CTO + 12820 s
Tube #3 is cooled to vent temp/vents	CTO + 13420 s
Tube #3 actuation	CTO + 13430 s
Tube #3 complete; DS13(down) gets +18V	CTO + 13460 s
Total time:	*13460 sec (224 min)*

11.2 Ground Ops

- No Ground Operations Support While on Orbit Necessary
  - Operations are completely autonomous once power is applied
  - RIGEX experiment does not include any telemetry or communication functions
    - Imperative that experiment be retrieved so that data can be processed on the ground
- Operations procedures at KSC
  - Only operation is to purge/pressurize tanks with N2
  - May potentially be done at integration facility
- Integration facility operation procedures are TBD

11.3 Open Issues

- Shuttle switch/light interface & Self test needs to be worked into the system and verified that RIGEX will feed back the correct input

12. Program Management

12.1 Master Schedule
12.2 Risk Areas
12.3 STP Documentation
12.4 Safety Documentation
12.5 ICD Discussion

12.1 Master Schedule

ID		Task Name	Duration	Start	Finish
1		STP Coordination / Documentation	382 days	Mon 6/27/05	Tue 12/12/06
2		RIGEX Kickoff	1 day	Fri 6/24/05	Fri 6/24/05
3		**Reviews**	**232 days**	**Tue 9/20/05**	**Wed 8/9/06**
4		RIGEX PDR	1 day	Tue 9/20/05	Tue 9/20/05
5		Safety Package 01 Submitted	1 day	Fri 10/21/05	Fri 10/21/05
6		Phase 0/1 Safety (TBD Dec 05)	1 day	Mon 12/5/05	Mon 12/5/05
7		Phase II Ground/GOWG (TBD Jan 06)	1 day	Mon 1/9/06	Mon 1/9/06
8		CDR (TBD Feb 06)	1 day	Thu 2/9/06	Thu 2/9/06
9		Safety Package II Submitted	1 day	Fri 1/13/06	Fri 1/13/06
10		Phase II Safety (TBD Mar 06)	1 day	Wed 3/1/06	Wed 3/1/06
11		Safety Package III Submitted	1 day	Wed 5/17/06	Wed 5/17/06
12		Phase III Safety (TBD Jul 06)	1 day	Mon 7/3/06	Mon 7/3/06
13		Phase III Ground (TBD Aug 06)	1 day	Wed 8/9/06	Wed 8/9/06
14		**Fabrication**	**92 days**	**Tue 6/28/05**	**Wed 11/2/05**
15		Ovens (if necessary)	20 days	Thu 10/6/05	Wed 11/2/05
16		Flight wiring harness	89 days	Tue 6/28/05	Fri 10/28/05
17		Structural	66 days	Tue 8/2/05	Tue 11/1/05

12.1 Master Schedule

ID		Task Name	Duration	Start	Finish
18		**Integrate/Assemble RIGEX**	**95 days**	**Thu 9/1/05**	**Wed 1/11/06**
19		**Inflation System**	**23 days**	**Fri 10/28/05**	**Tue 11/29/05**
20		Integrate Pressure System	23 days	Fri 10/28/05	Tue 11/29/05
21		**Structure**	**54 days**	**Fri 10/28/05**	**Wed 1/11/06**
22		Assemble/Integrate Structure	12 days	Tue 11/1/05	Wed 11/16/05
23		Assemble/Integrate Ovens	17 days	Fri 10/28/05	Mon 11/21/05
24		Integrate Sensors	16 days	Mon 11/21/05	Mon 12/12/05
25		Integrate Cameras	16 days	Wed 12/21/05	Wed 1/11/06
26		**Electrical/Power**	**14 days**	**Thu 12/1/05**	**Tue 12/20/05**
27		Integrate flight wiring harness	14 days	Thu 12/1/05	Tue 12/20/05
28		Integrate Environmental Heaters (CPU,Cameras)	7 days	Mon 12/12/05	Tue 12/20/05
29		**Command & Data Handling**	**73 days**	**Thu 9/1/05**	**Mon 12/12/05**
30		Assemble/Integrate Computer	16 days	Mon 11/21/05	Mon 12/12/05
31		**Modify Computer Code**	**58 days**	**Thu 9/1/05**	**Mon 11/21/05**
32		Add Heat/Cool Profiles	1 day	Mon 10/3/05	Mon 10/3/05
33		Develop health/verification test profile	23 days	Thu 9/1/05	Mon 10/3/05
34		Integrate into computer stack	8 days	Thu 11/10/05	Mon 11/21/05
35		**Initial Part Testing**	**145 days**	**Fri 7/1/05**	**Thu 1/19/06**
36		End-to-end avionics/software test	74 days	Fri 7/1/05	Wed 10/12/05
37		Heater box and 1 tube vibration testing	43 days	Mon 9/12/05	Wed 11/9/05
38		Pressure system leak testing	37 days	Wed 11/30/05	Thu 1/19/06

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12.1 Master Schedule

ID		Task Name	Duration	Start	Finish
39		**Initial Full-up RIGEX testing**	**44 days**	**Thu 1/12/06**	**Tue 3/14/06**
40		3-tube deployment test, ambient	7 days	Thu 1/12/06	Fri 1/20/06
41		System leak test	1 day	Mon 1/23/06	Mon 1/23/06
42		3-axis vibration testing	7 days	Tue 1/24/06	Wed 2/1/06
43		System leak test	1 day	Thu 2/2/06	Thu 2/2/06
44		3-tube deployment test, ambient	7 days	Fri 2/3/06	Mon 2/13/06
45		3-tube deployment test thermal vacuum	7 days	Tue 2/14/06	Wed 2/22/06
46			7 days	Thu 2/23/06	Fri 3/3/06
47		End-End health/verification test, ambient	7 days	Mon 3/6/06	Tue 3/14/06
48		End-End health/verification test, vacuum (if necessary)	7 days	Thu 1/12/06	Fri 1/20/06
49		Electromagnetic Testing (dates TBD)	1 day	Thu 1/12/06	Thu 1/12/06
50		Interface Verification Test (dates TBD)	1 day	Thu 1/12/06	Thu 1/12/06
51		AFIT Graduation	1 day	Tue 3/21/06	Tue 3/21/06
52		Final RIGEX modification (from tests, if necessary)	25 days	Fri 6/24/05	Thu 7/28/05
53		**Final RIGEX test (if necessary)**	**18 days**	**Wed 7/5/06**	**Fri 7/28/06**
54		End-End health/verification test	18 days	Wed 7/5/06	Fri 7/28/06
55		Delivery and prep (TBD Sept 06)	1 day	Mon 9/11/06	Mon 9/11/06
56		AFIT Graduation	1 day	Wed 9/13/06	Wed 9/13/06
57		Initial Launch Capability (NET 7 Dec 06)	1 day	Thu 12/7/06	Thu 12/7/06
58		Launcher Removal (Dates TBD)	1 day	Thu 2/1/07	Thu 2/1/07

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12.2 Risk Areas

- Schedule
  - Limited number of Master's students with unique thesis / graduation timeline creates complications with continuity and scheduling
  - Environmental testing schedule / facilities remain unknown at this point
- Risk Mitigation
  - Principle Investigator, Dr. Cobb, maintains RIGEX program continuity
  - Incoming class (Sept 05 – Mar 07) provides potential source of additional students for RIGEX team
  - Working with AFRL/ML to identify testing facilities

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12.3 STP Documentation

- Completed
  - DD Form 1721 *Space Test Program Flight Request*
    - Completed and signed 2 November 2004
  - *Memorandum of Agreement Between SMC/STP and AFIT for RIGEX* (MoA)
    - Completed and signed 13 May 2005
  - *STP Payload Requirements Document for RIGEX* (PRD)
    - Updates made and sent to STP for approval 18 August 2005
  - RIGEX Export Classification Document
    - Final copy mailed to STP for approval 1 September 2005
  - Preliminary Design Review (PDR)
    - Completed in three more slides, 20 September 2005
- Future Documents Required
  - Payload Integration Plan (PIP)
  - Critical Design Review (CDR)
  - RIGEX Thermal Model
  - RIGEX Structural Model

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12.4 Safety Documentation

- Future Documents Required
  - Safety Data Package (SDP)
    - Submitted 45 days prior to all three Payload Safety Reviews (SR)
    - Flight SDP submitted for Phase 0/I SR
    - Flight and Ground SDP submitted for Phase II and Phase III SR
  - Structural Verification Plan (SVP)
  - Fracture Control Plan (FCP)
  - Mechanical Systems Verification Plan (MSVP)

12.5 ICD Discussion

- RIGEX Mounting Plate has CAPE bolt hole pattern
- Electrical interface has been discussed at weekly meetings
  - Exact connector and location TBD
- Clocking of RIGEX on CAPE unknown

Appendix B: Evolution of the RIGEX Inflation Subsystem

The RIGEX inflation system has undergone many changes since its first conceptual plan. The initial design was largely driven by volume constraints and involved one small, highly pressurized cylinder that branched off to inflate all three tubes. This design was plausible but created a safety concern due to its highly pressurized components. It also left no room for error. If the pressure system had any leaks, none of the three tubes would inflate and the whole experiment objective would fail. Therefore, when RIGEX was changed from the GAS canister to CAPE, a change that allowed its payloads to obtain power directly from the Shuttle, the internal battery box was eliminated and the space was instead used as an inflation system bay. The initial redesign efforts of the inflation system were completed by Moeller in 2005 (27). He stepped through a set of pressure equations and completed testing in order to determine the size of a new pressure cylinder. This new cylinder was much bigger than the old version and, therefore, would only require to be filled to an ambient 14.7 psi. Also, three of the new cylinders would fit within the inner RIGEX bay so that each Sub-Tg tube could have its own identical inflation system. With this new design, if one inflation system failed the other two tubes could still be effectively deployed. The initial inflation system concept can be seen in Figure B.1. Figure B.2 shows the prototype assembly of Moeller's modified system mounted to a RIGEX quarter structure mock-up. The modified pressure cylinder had been chosen, but finalization of all other components and full integration of the inflation system into the RIGEX detailed design remained.

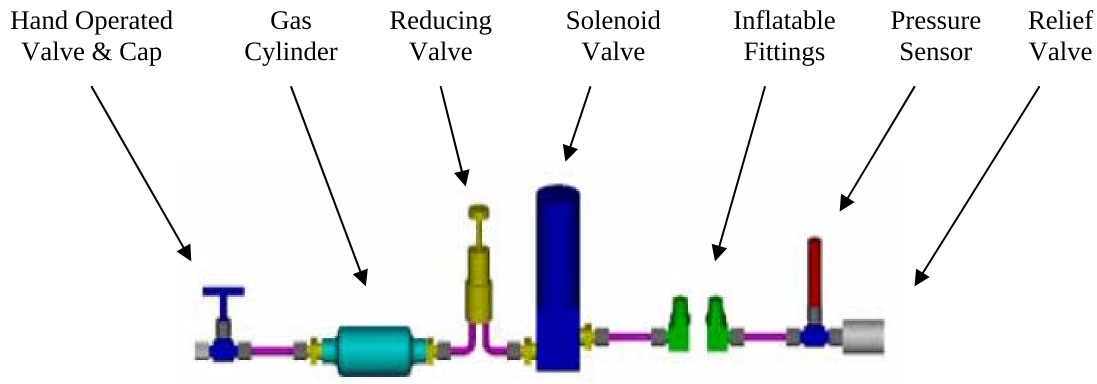


Figure B.1   Initial Inflation System Conceptual Design (9)

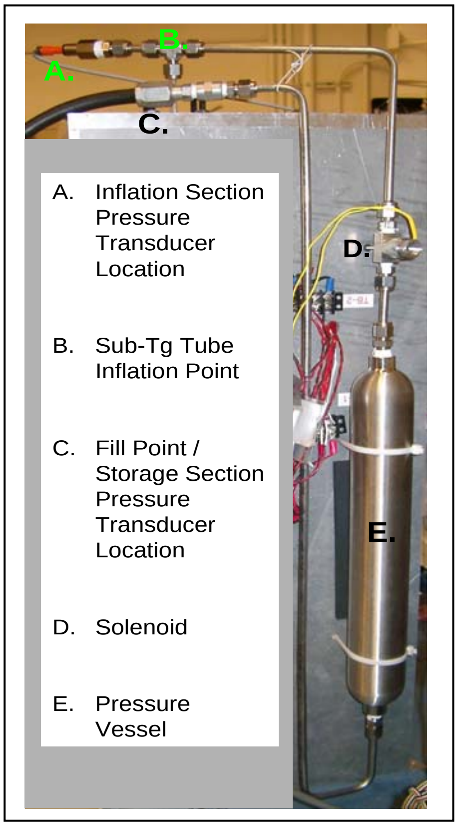


Figure B.2   Prototype Assembly of Modified Inflation System (27)

B.1 Component Selection

With the pressure cylinder chosen, a structural support system to hold it in place had to be designed. To secure all three cylinders inside the inner bay, a set of inflation system plates was designed. These plates were analyzed using the equation $\vec{F} = m \cdot \vec{a}$. Where m was the mass of the cylinders, $\vec{a}$ was the acceleration imparted due to a 30g dynamic environment, and $\vec{F}$ was the resultant force imparted on the inflation system plates and bolts. The entire mass of the three cylinders was applied to one of the structural plates in order to represent a worst case scenario. Using yield strength, the factors of safety obtained were greater than 20, therefore easily meeting the 1.5 standard.

After the structural plates were designed, a set of pressure transducers had to be found that would record data from 0-15 psi and withstand spaceflight loading and environment conditions. Taber Industries Series 2 pressure transducers were chosen due to their excellent performance, 5" long length, and resistance to shock, vibration, and cold temperatures (40). Six M2911C150AEFAAA1 pressure transducers were ordered and are awaiting assembly in the AFIT lab. The back shell and all connecting cables must be assembled separately and have yet to be ordered.

The last item missing from the inflation system was a proper fill valve. The Swagelok SS-43GF2-A 2-Way ball valve was chosen and connected to the system via a pipe tee (41). The angled version was picked for ease of access in the tight inner bay space. The system will be purged of air using the AFIT vacuum pump available in the Vibrations Lab. Nitrogen will then be added to obtain a pressure of 14.7 psi (ambient) before shipping RIGEX to be integrated with CAPE.

B.2 Detailed Block Diagram

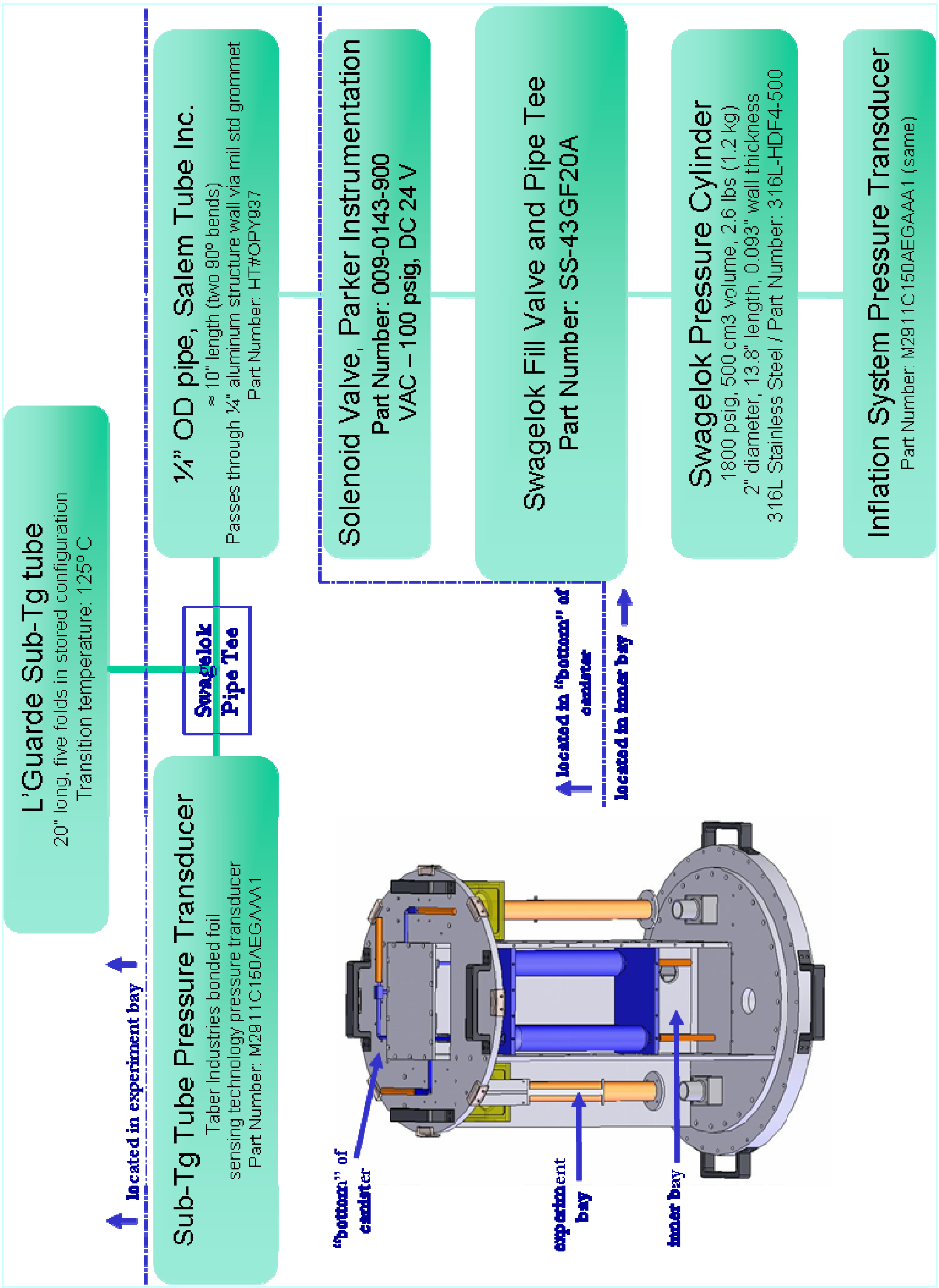


Figure B.3 RIGEX Inflation System Detailed Block Diagram

B.3 Integration into RIGEX Detailed Design

After all parts had been picked, the newly designed inflation system had to be placed into the RIGEX detailed design. A schematic of the concept was made and then integrated into the RIGEX SolidWorks drawings by Goodwin (14). The final result is shown in Figure B.4.

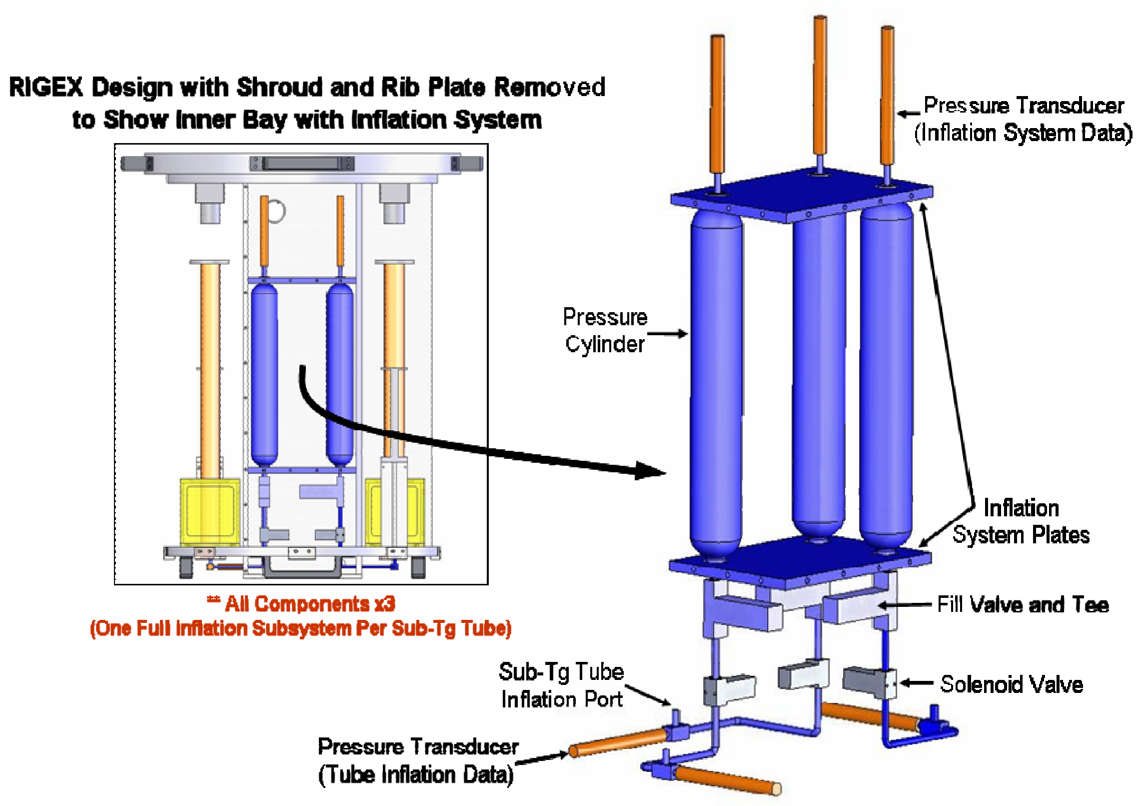
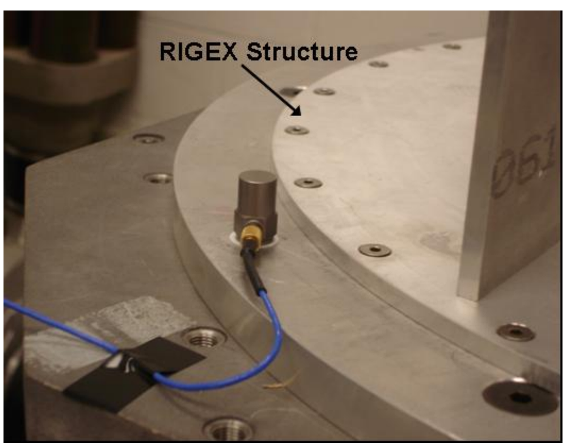


Figure B.4 Inflation System Detailed Design Drawings

Due to the complex routing of the inflation system tubes, inclusion of the inflation system should be one of the first items in the assembly procedure. Two of the structure ribs can be put together initially and then held in place with the pressure system plates and pressure cylinders. Circular pieces of Viton, cut to fit, will be placed between the ends of each pressure cylinder and the inflation system plates. The routing of the inflation system tubes, along with all connectors, tees and valves can then be added. The inflation system pressure transducers should be added before the top plate is bolted onto the structure. The very sensitive Sub-Tg tube pressure transducers should be left off until absolutely necessary at the end of the assembly. This way any inadvertent exposure or touching can be avoided while the other subsystems are being added.

Appendix C: Accelerometer Locations for Random Vibration Testing

Eight PCB Piezotronics Inc. shear accelerometers were used for data acquisition during vibration testing. Accelerometer #1, Model #J353B01, was calibrated using an acceleration calibration standard over its 1-5000 Hz frequency range. This accelerometer was used as the control and was placed directly inline with the drive system for unity feedback control. For the vertical vibe head setup to test the Z axis, the control accelerometer was placed on the interface between the RIGEX structure and the vibe table. For the horizontal vibe head setup to test the X and Y axes, this accelerometer was placed on the edge of the floating sliptable plate. The control accelerometer was mounted using a threaded stud, supplied with the product. The placement of this accelerometer, in both the vertical and horizontal configurations, is shown in Figure C.1.



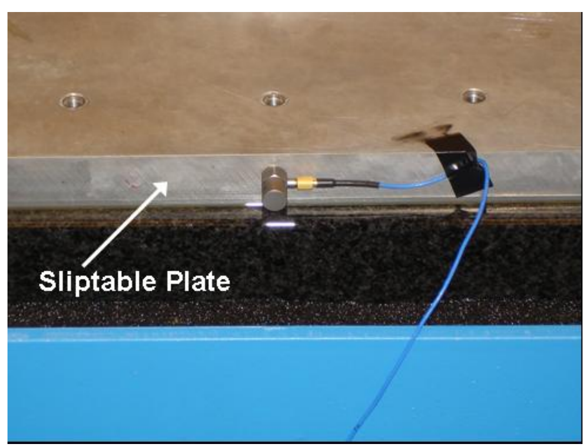


Figure C.1   Control Accelerometer Locations: Vertical and Horizontal

Model #352C22, 1-8000 Hz frequency range accelerometers were used for seven other data acquisition locations. These accelerometers were all mounted with a thin layer of beeswax and a small piece of electrical tape to hold the connecting wire in place during vibration. Accelerometer #1 was the control, #2 thru #8 were data acquisition accelerometers specified by their location as follows:

#2 Heater Box Long Side (Front)
#3 Heater Box Short Side
#4 Heater Box Top Flap
#5 Sub-Tg Tube Flange (Free End)
#6 Structure Circular Heater Box Mounting Plate
#7 Structure Square Plate
#8 Structure Rib Plate

Figures C.2, C.3, and C.4 show the location of each acquisition accelerometer on the RIGEX structure. These positions were kept constant throughout testing.

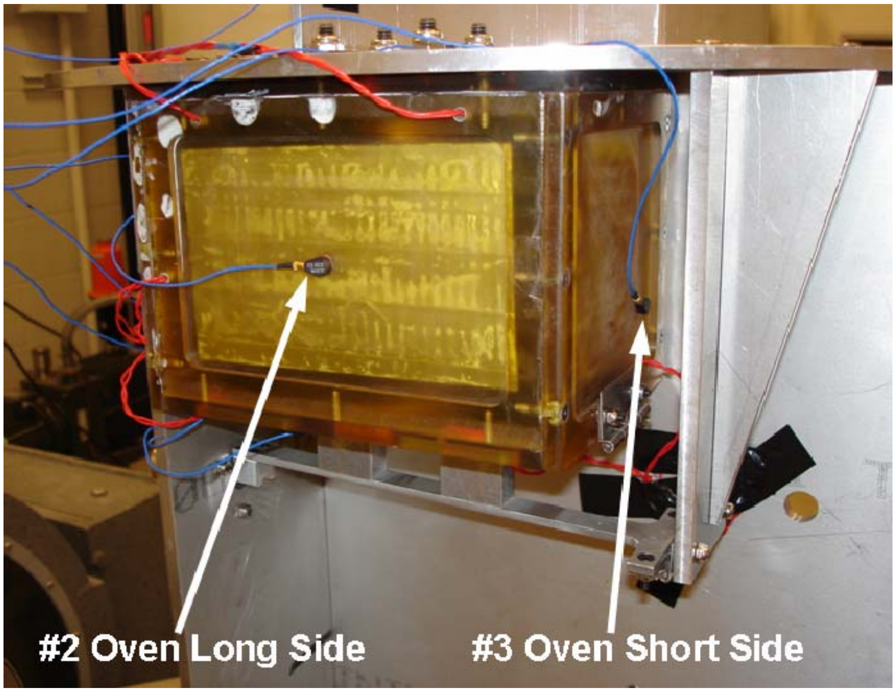


Figure C.2 Position of Accelerometers #2 and #3

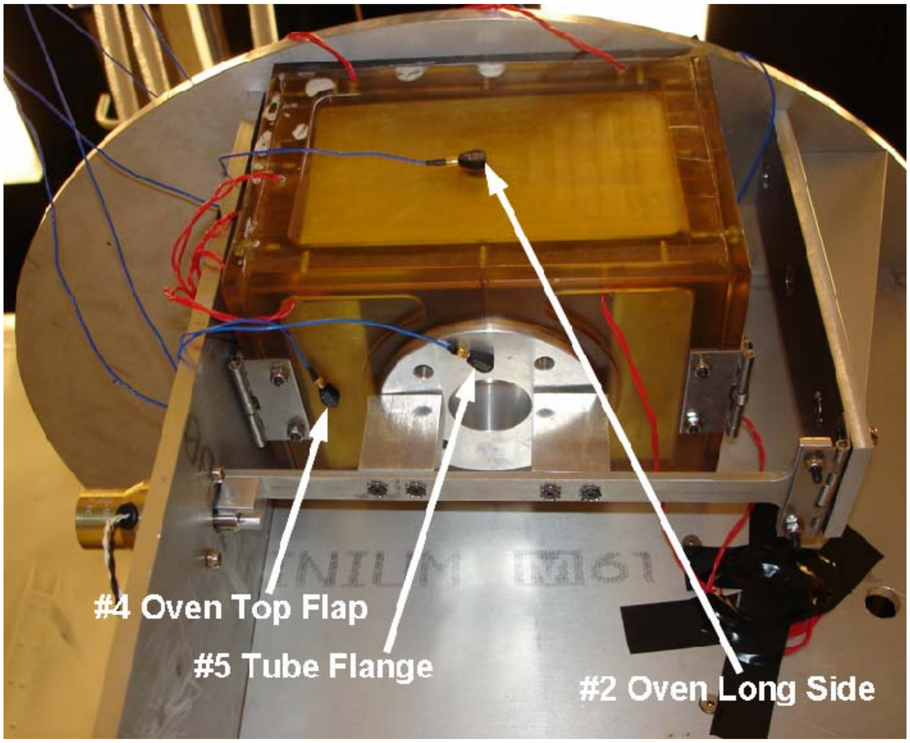


Figure C.3 Position of Accelerometers #2, #4, and #5

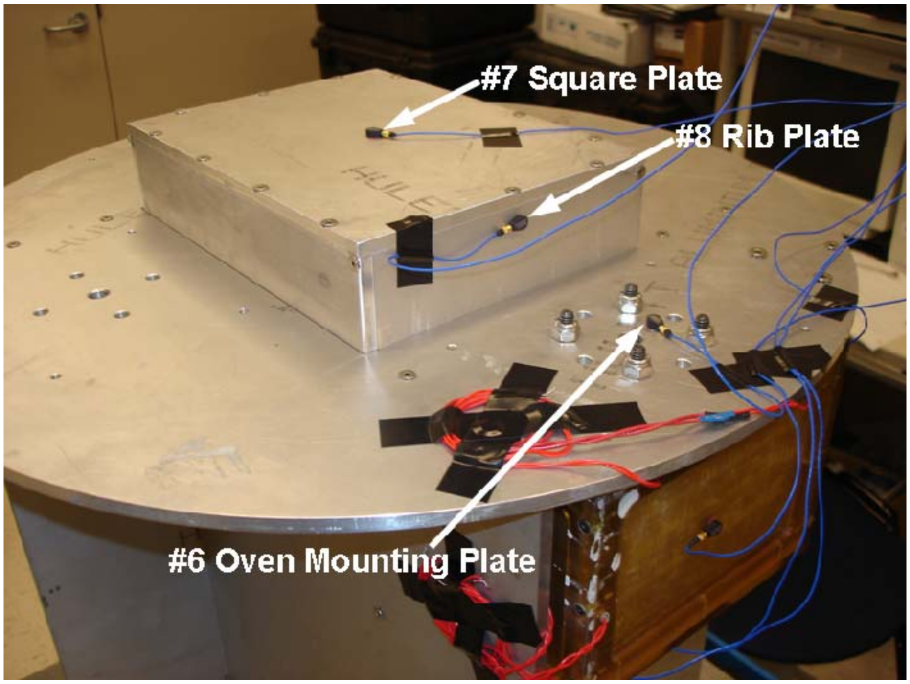


Figure C.4 Position of Accelerometers #6, #7, and #8

Appendix D: Comprehensive Random Vibration Test Results

The *initial* sine sweep and *final* sine sweep test profiles for each axis are included in Figures D.1, 10, and 19. The random vibration test profiles for each axis are included in Figures D.2, 11, and 20. Each of these graphs includes the MB Dynamics Vibration controller target profile as well as the actual signal produced. The sine sweep graphs are a time domain plot of the signal produced, whereas the random vibration graphs show a frequency domain snapshot of the signal at one time increment during the test. This snapshot is shown as an indication of the general fit of the signal to the profile.

The frequency response, shown as PSDs, recorded by each of the seven data acquisition accelerometers are presented in the following series of figures: Figures D.3-9 for the X axis test, Figures D.12-18 for the Y axis test, and Figures D.21-27 for the Z axis test. Each graph includes baseline data recorded as an *initial* PSD, *final* PSD data recorded after the random vibration profile was accomplished, and *repaired* PSD data gathered after all bolts on the structure were re-tightened. The *repaired* PSD data was taken in order to assess and eliminate the effect of loosened bolts on the results.

The X and Y axis testing was done with the vibe head in the horizontal position, attached to a sliptable. To specify which RIGEX axis, X or Y, was being tested, the desired axis was positioned in alignment with the vector normal to the vibe head surface. The Z axis testing was done with the vibe head in the vertical position.

D.1 X Axis Results

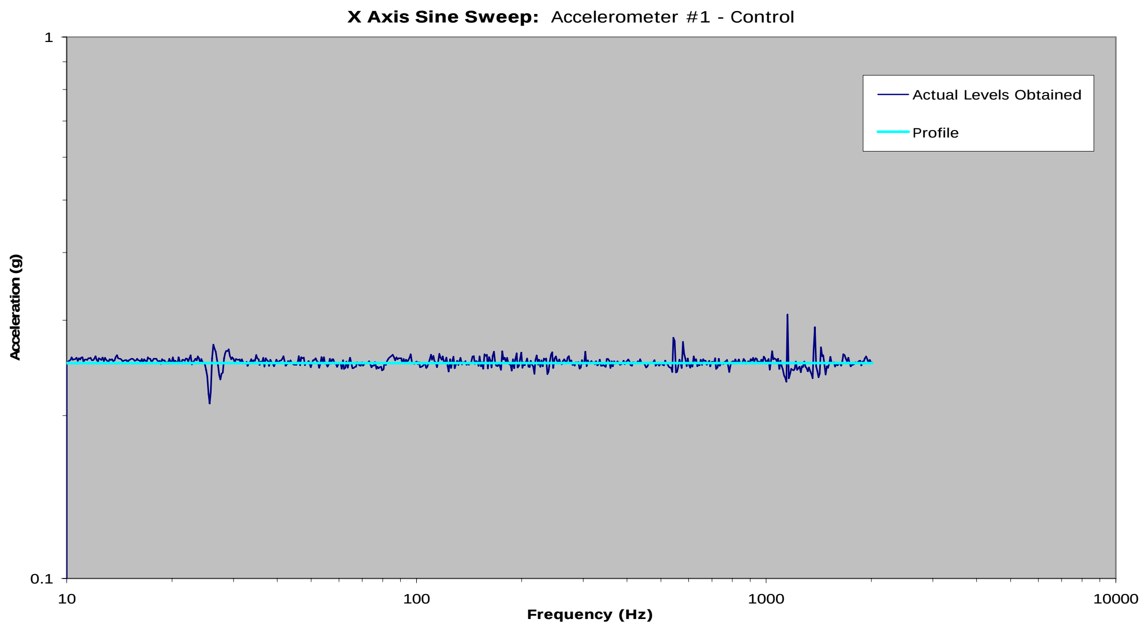


Figure D.1 X Axis Sine Sweep Test Profile

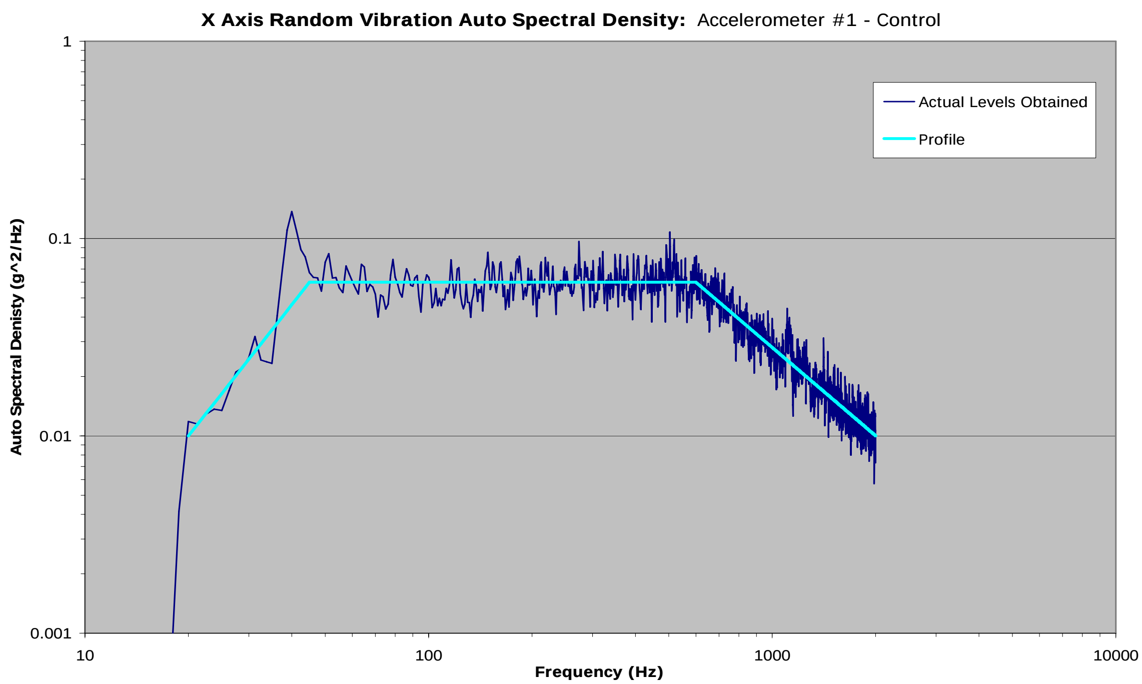


Figure D.2 X Axis Random Vibration Test Profile

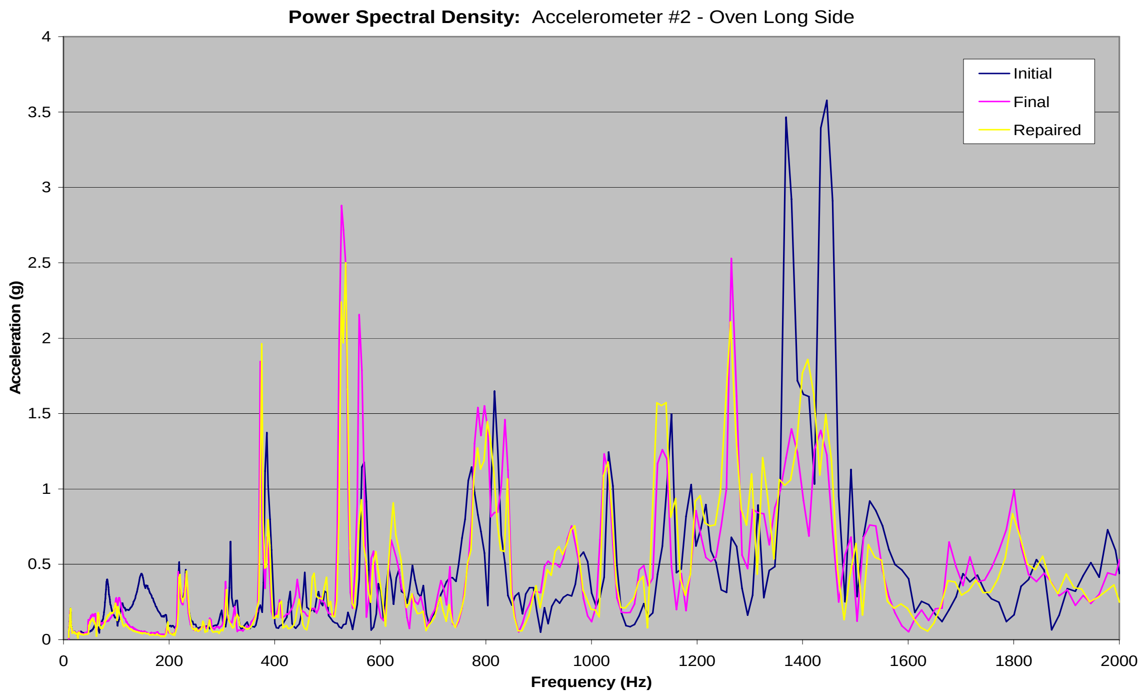


Figure D.3 X Axis Random Vibration Accelerometer #2 PSDs

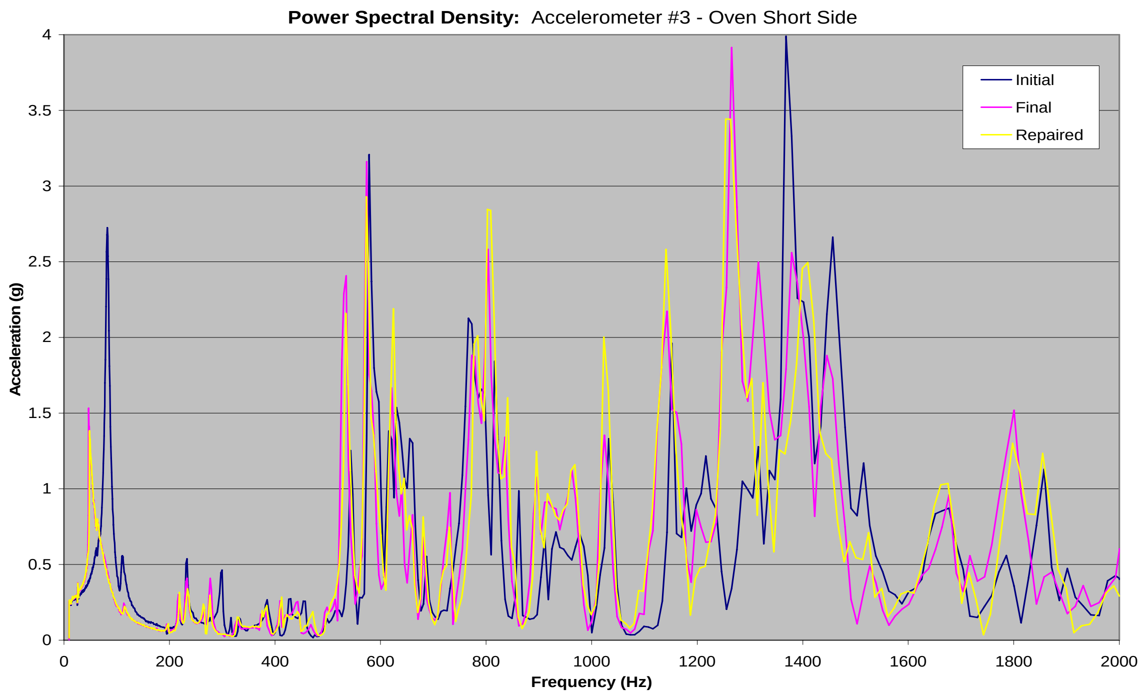


Figure D.4 X Axis Random Vibration Accelerometer #3 PSDs

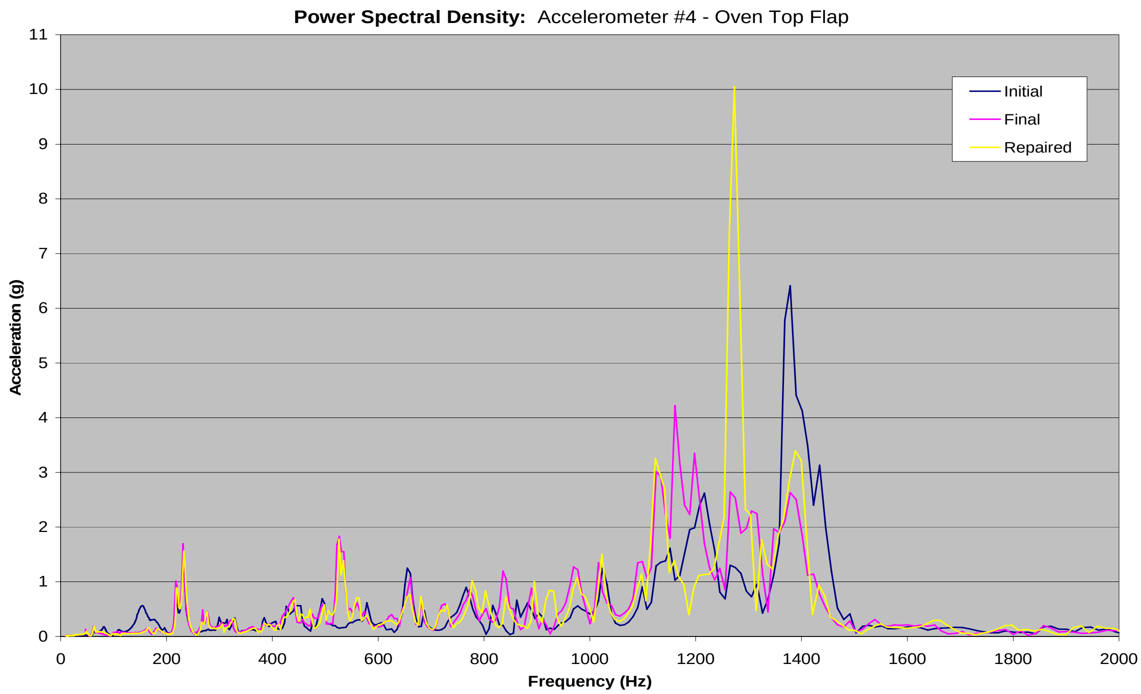


Figure D.5 X Axis Random Vibration Accelerometer #4 PSDs

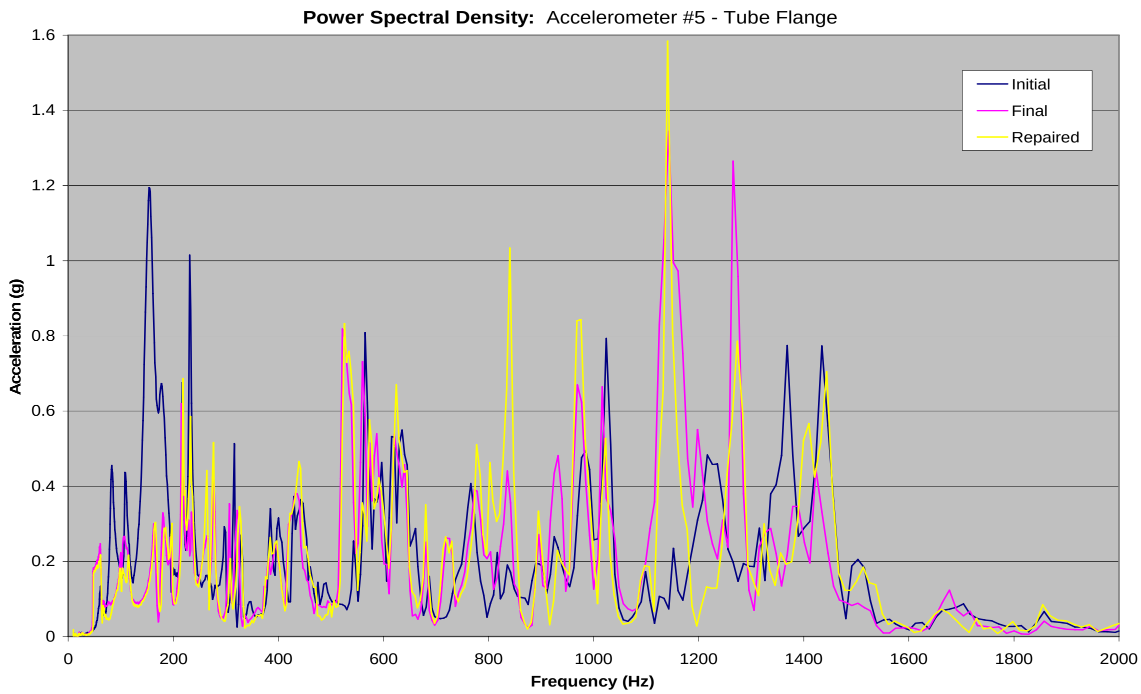


Figure D.6 X Axis Random Vibration Accelerometer #5 PSDs

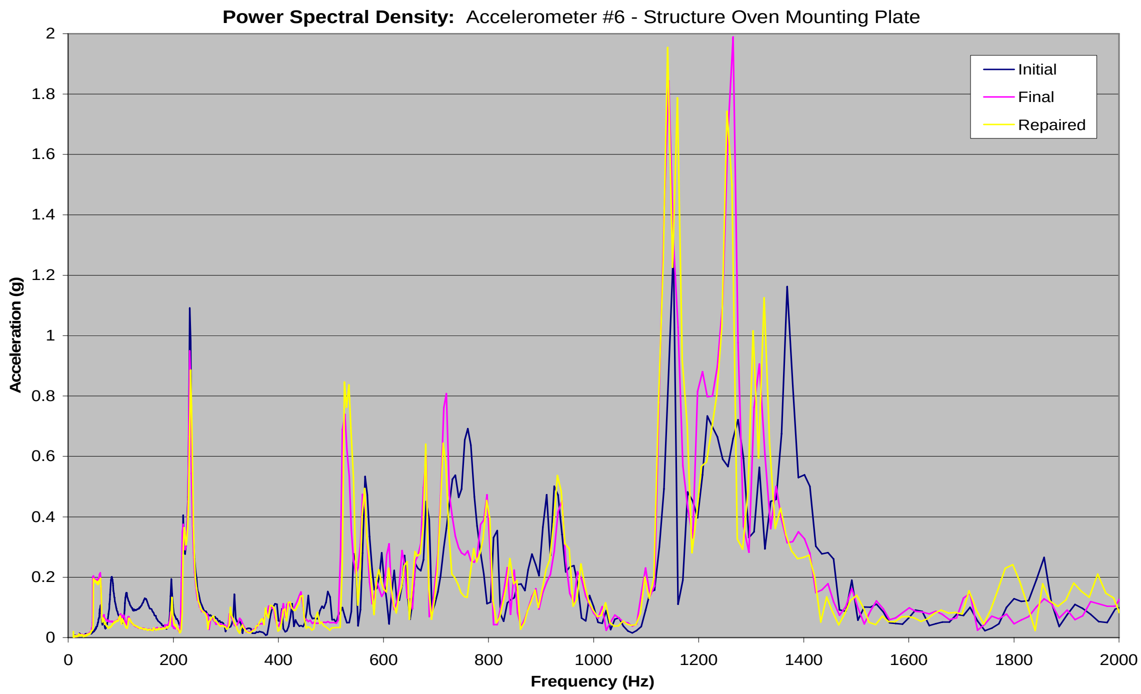


Figure D.7 X Axis Random Vibration Accelerometer #6 PSDs

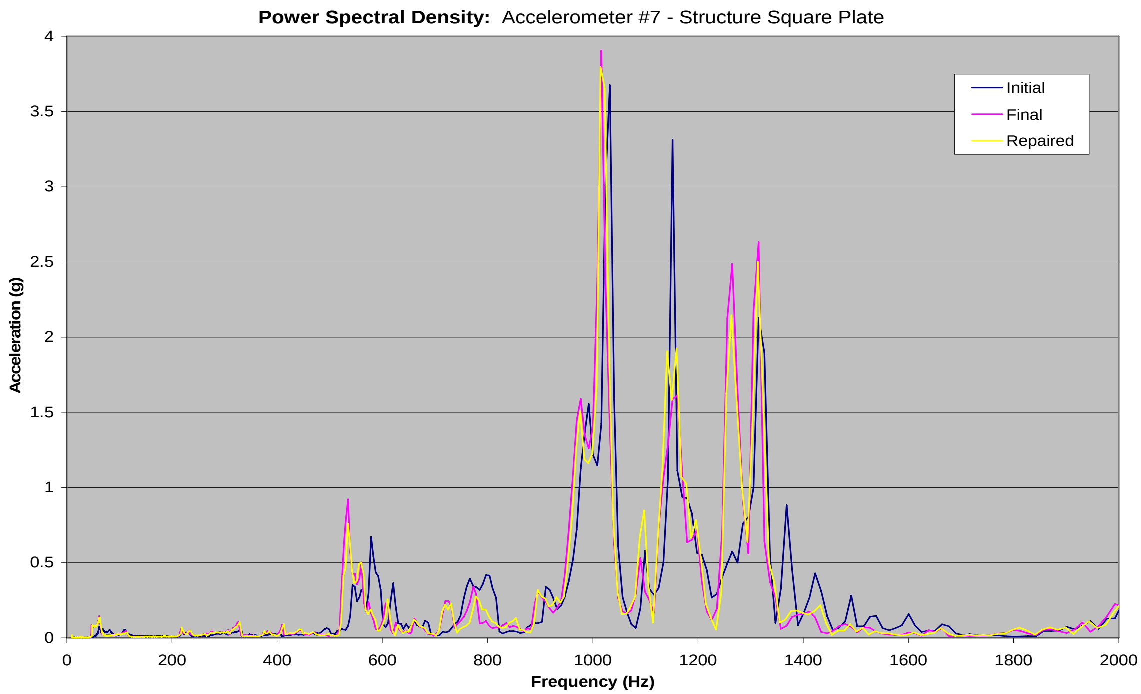


Figure D.8 X Axis Random Vibration Accelerometer #7 PSDs

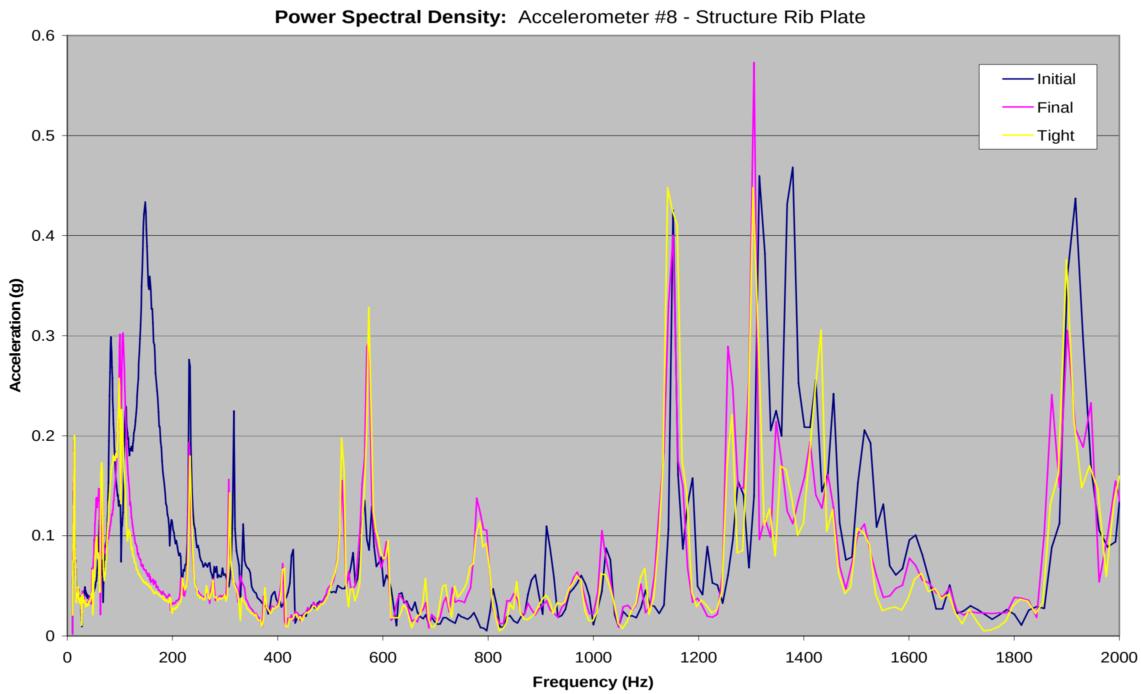


Figure D.9 X Axis Random Vibration Accelerometer #8 PSDs

D.2 Y Axis Results

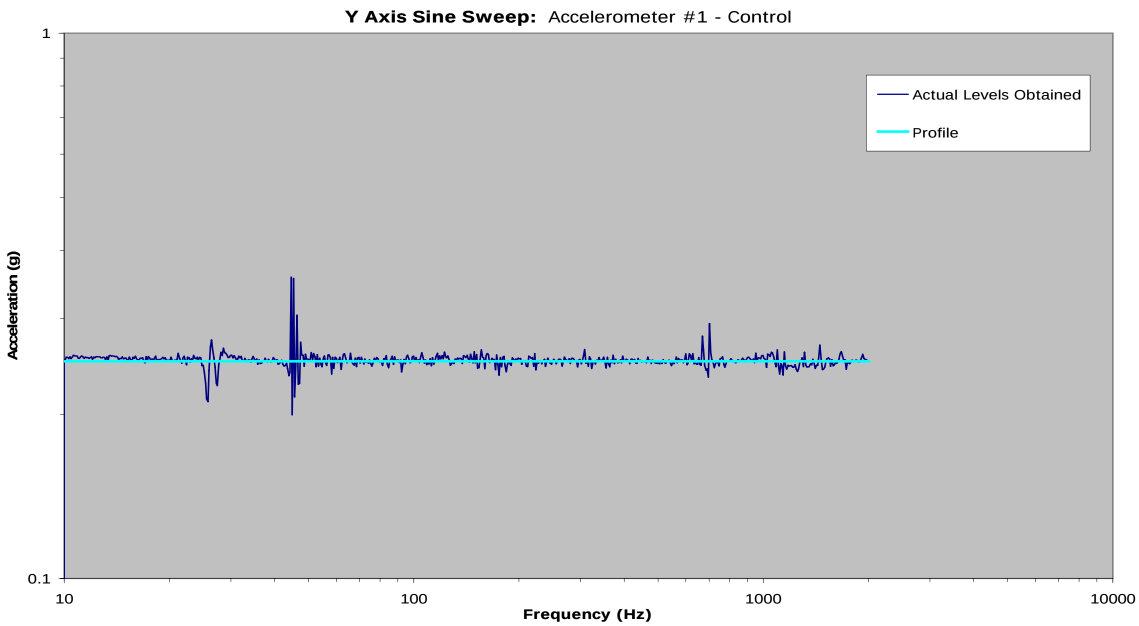


Figure D.10 Y Axis Sine Sweep Test Profile

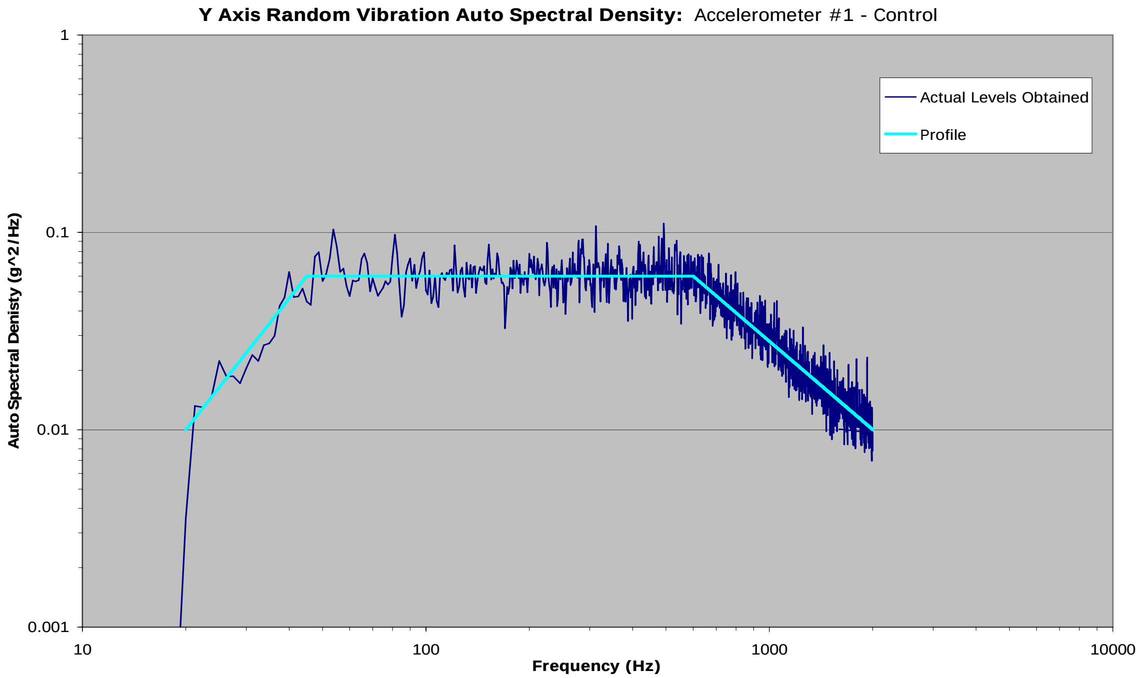


Figure D.11 Y Axis Random Vibration Test Profile

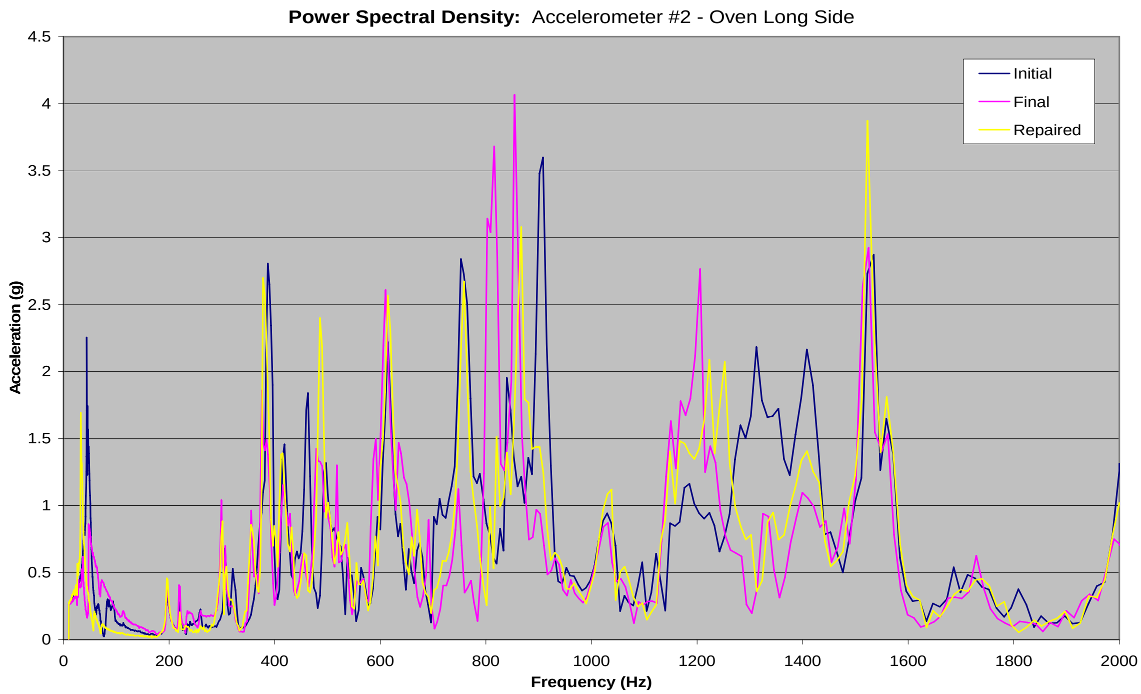


Figure D.12 Y Axis Random Vibration Accelerometer #2 PSDs

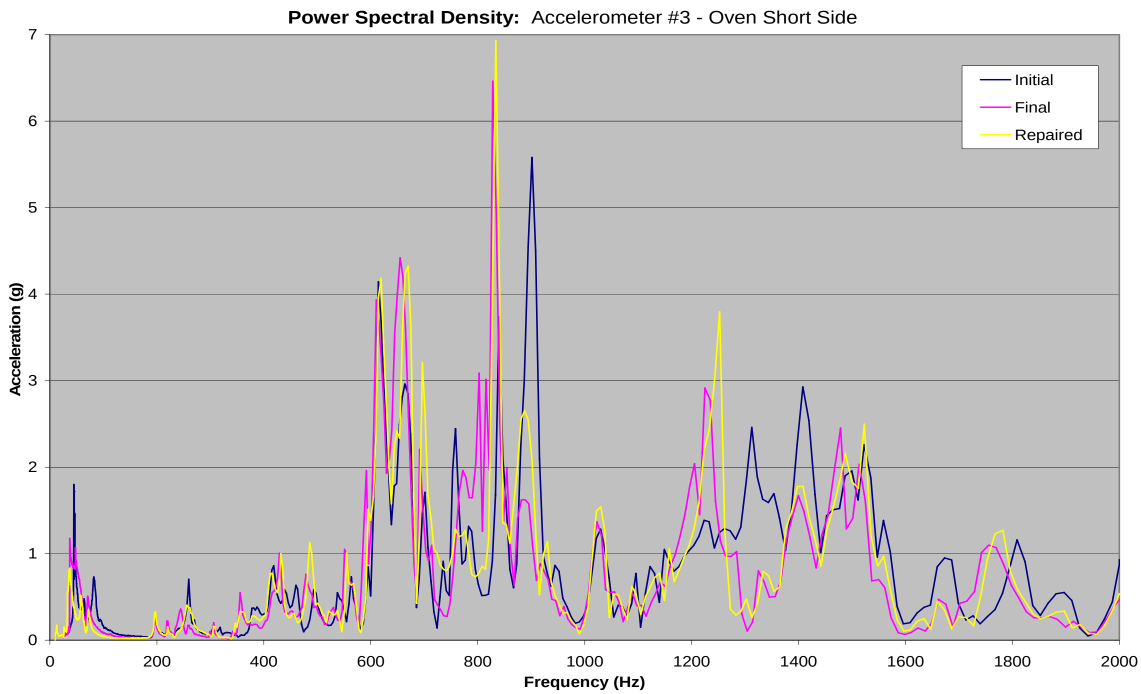


Figure D.13 Y Axis Random Vibration Accelerometer #3 PSDs

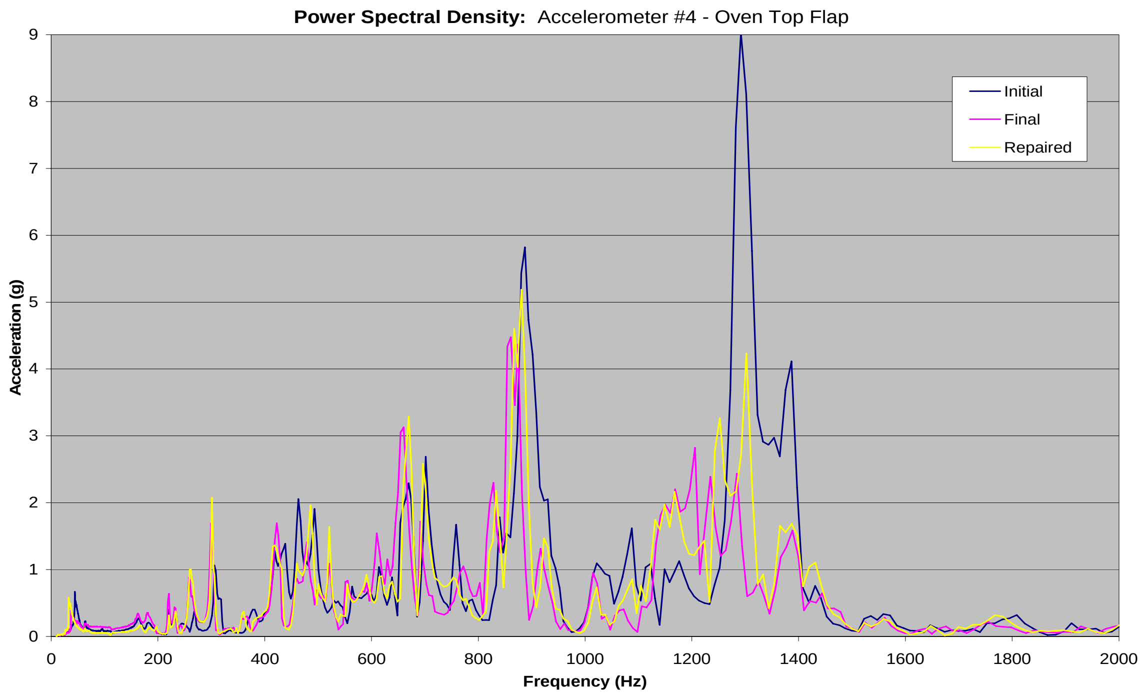


Figure D.14 Y Axis Random Vibration Accelerometer #4 PSDs

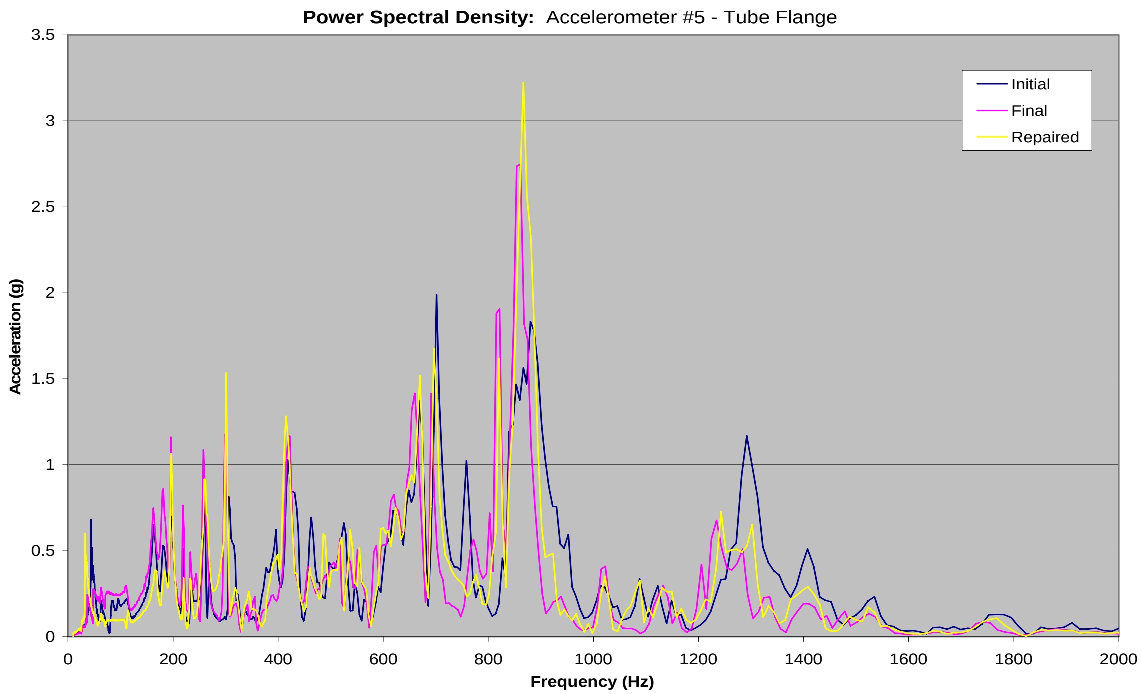


Figure D.15 Y Axis Random Vibration Accelerometer #5 PSDs

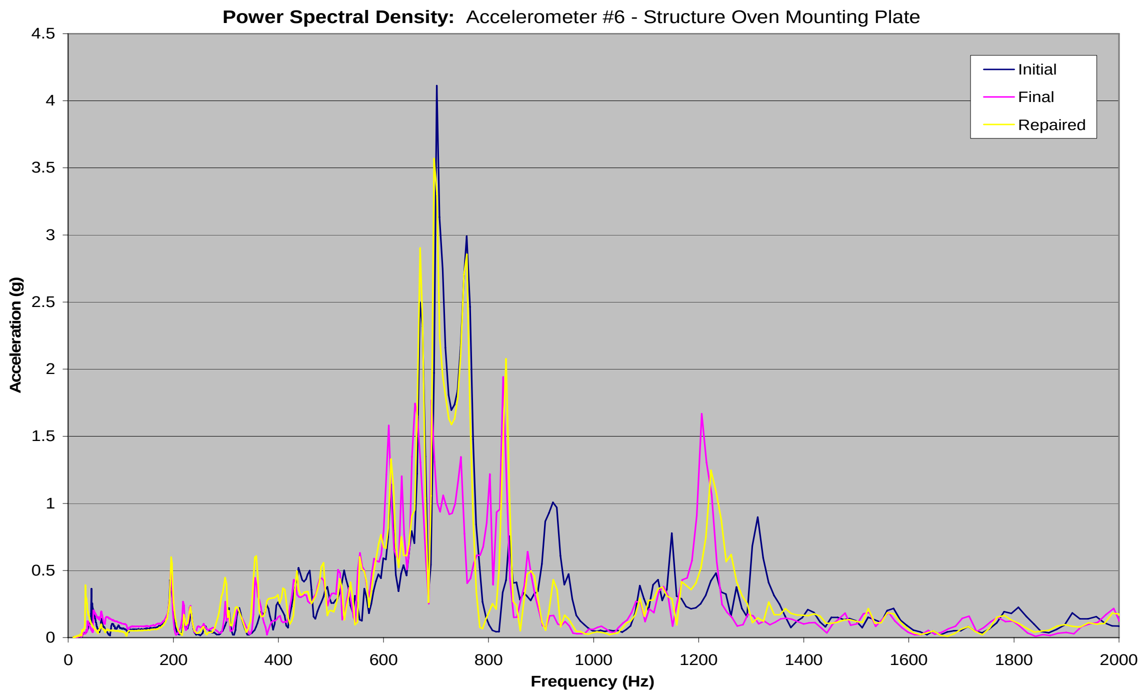


Figure D.16 Y Axis Random Vibration Accelerometer #6 PSDs

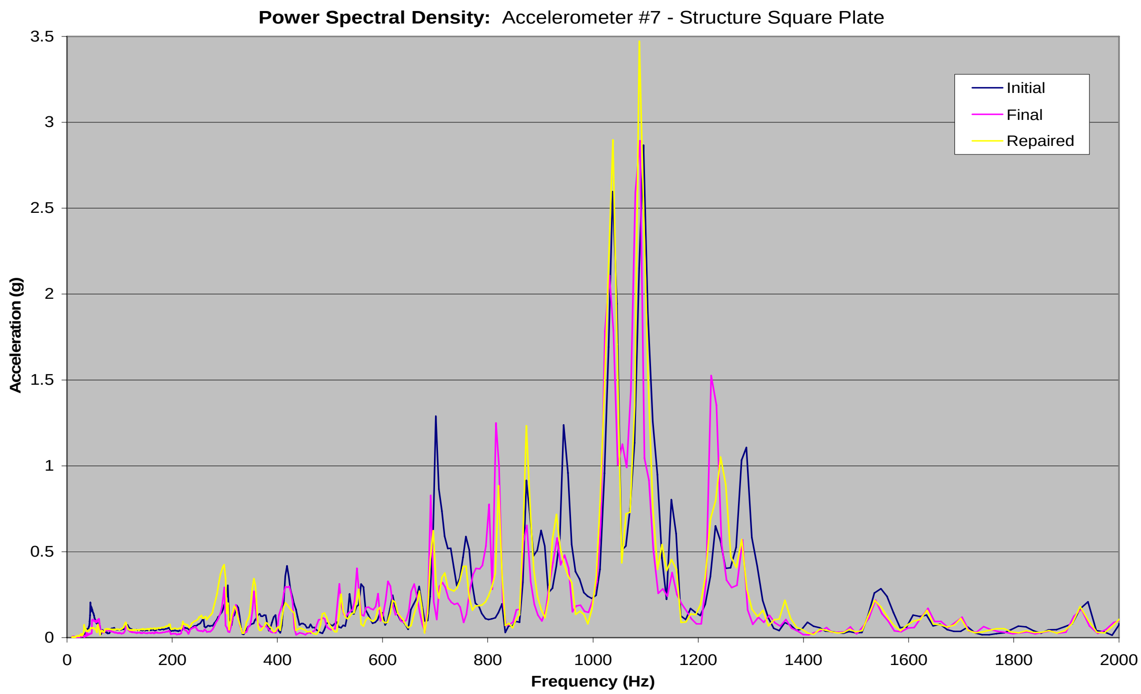


Figure D.17 Y Axis Random Vibration Accelerometer #7 PSDs

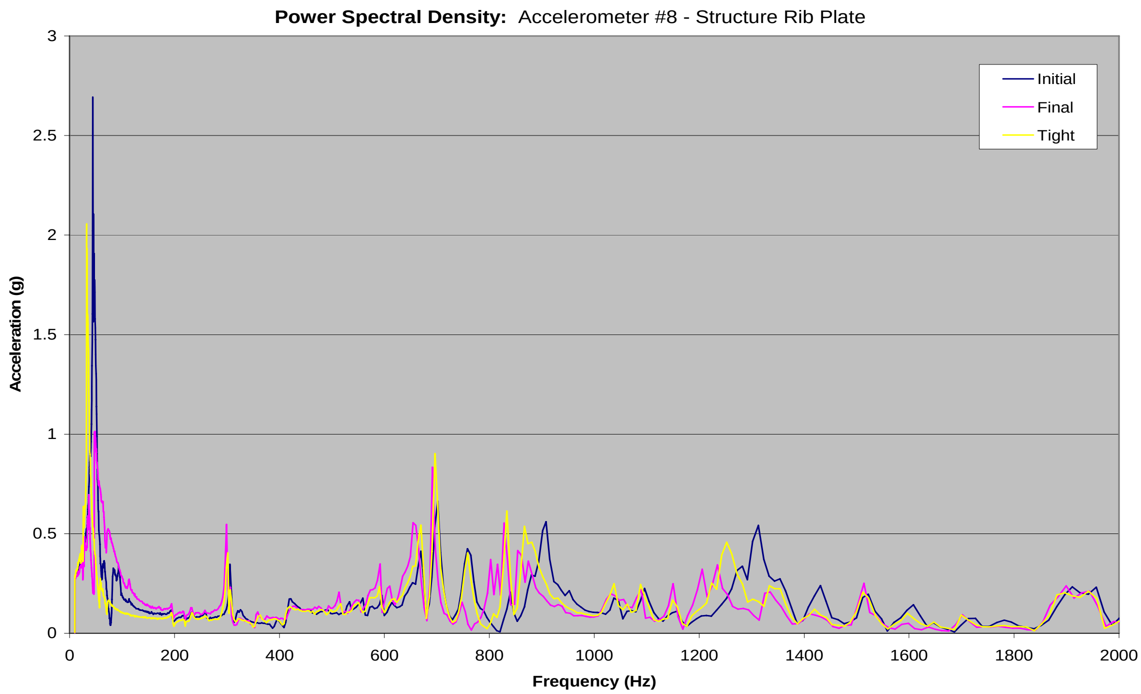


Figure D.18 Y Axis Random Vibration Accelerometer #8 PSDs

D.3 Z Axis Results

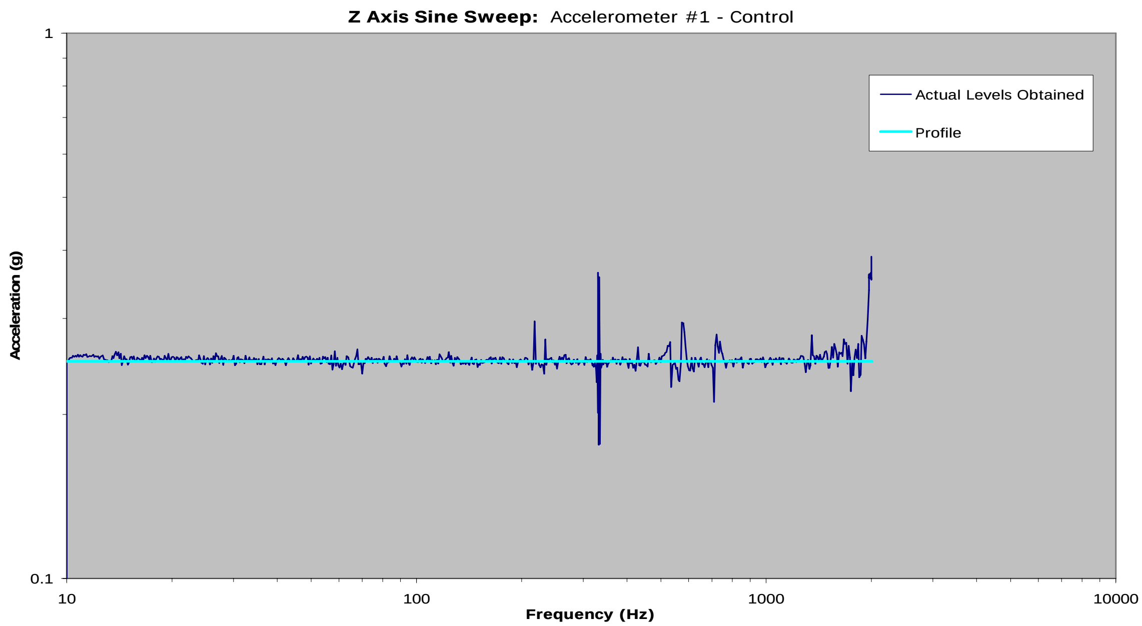


Figure D.19 Z Axis Sine Sweep Test Profile

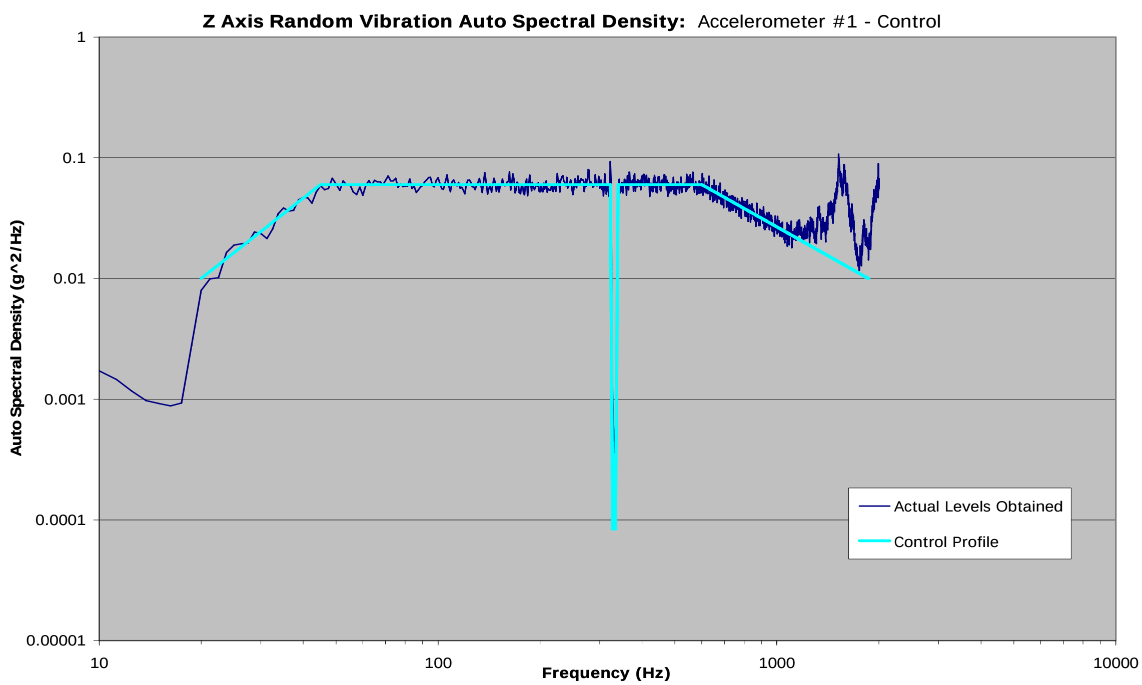


Figure D.20 Z Axis Random Vibration Test Profile

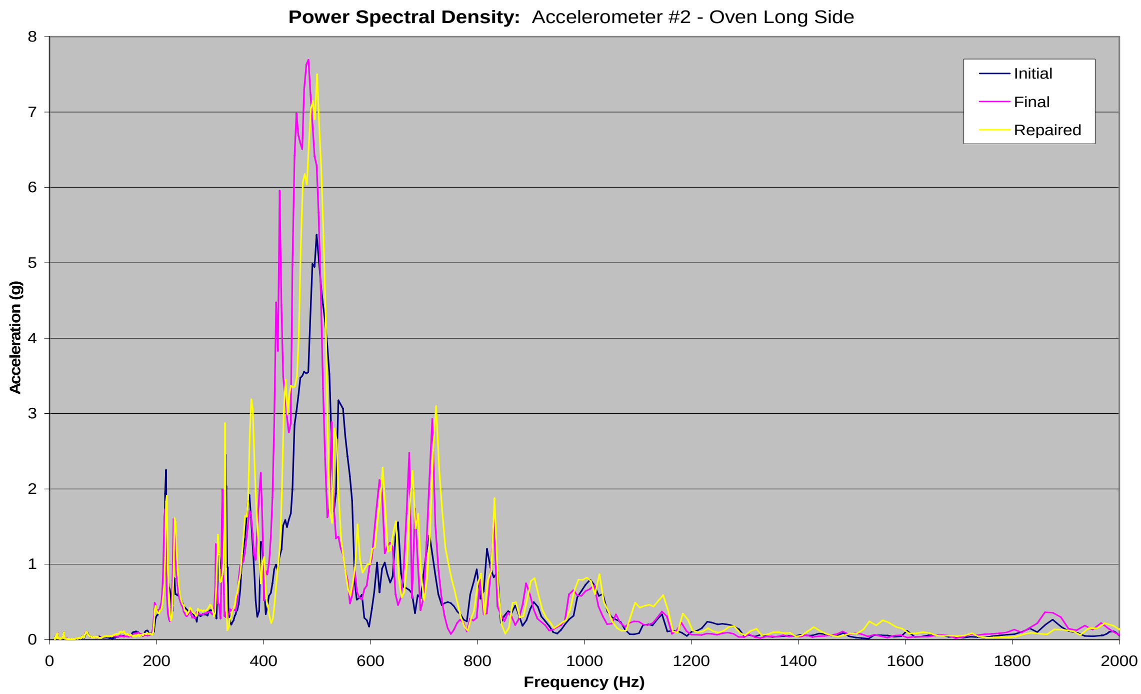


Figure D.21   Z Axis Random Vibration Accelerometer #2 PSDs

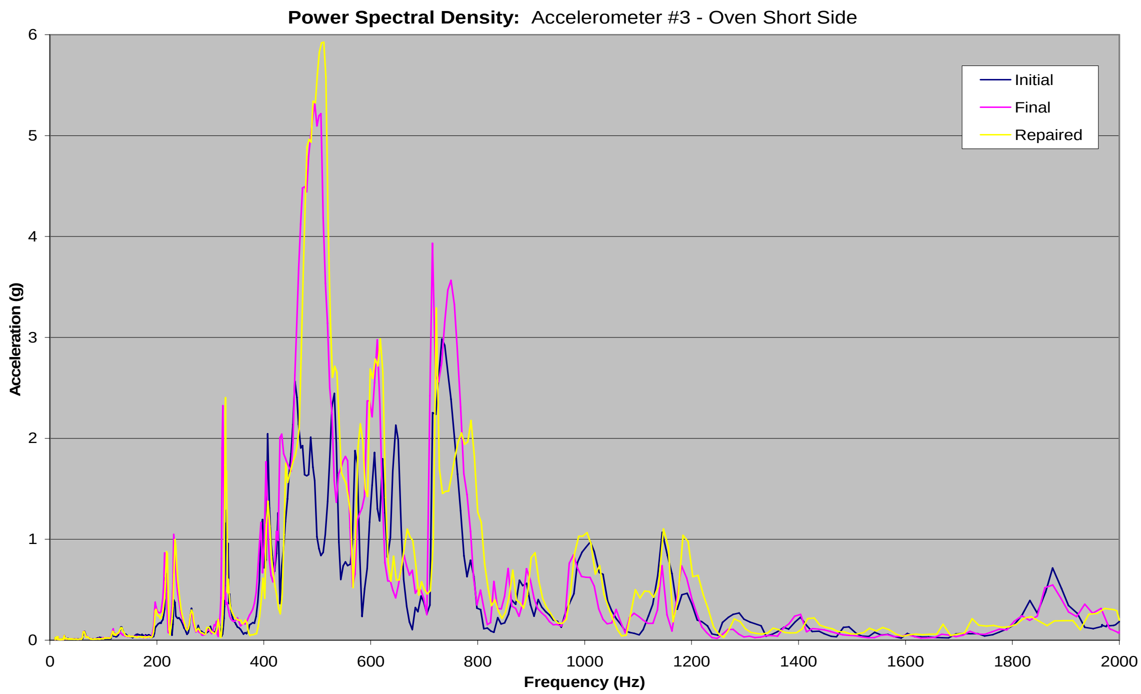


Figure D.22   Z Axis Random Vibration Accelerometer #3 PSDs

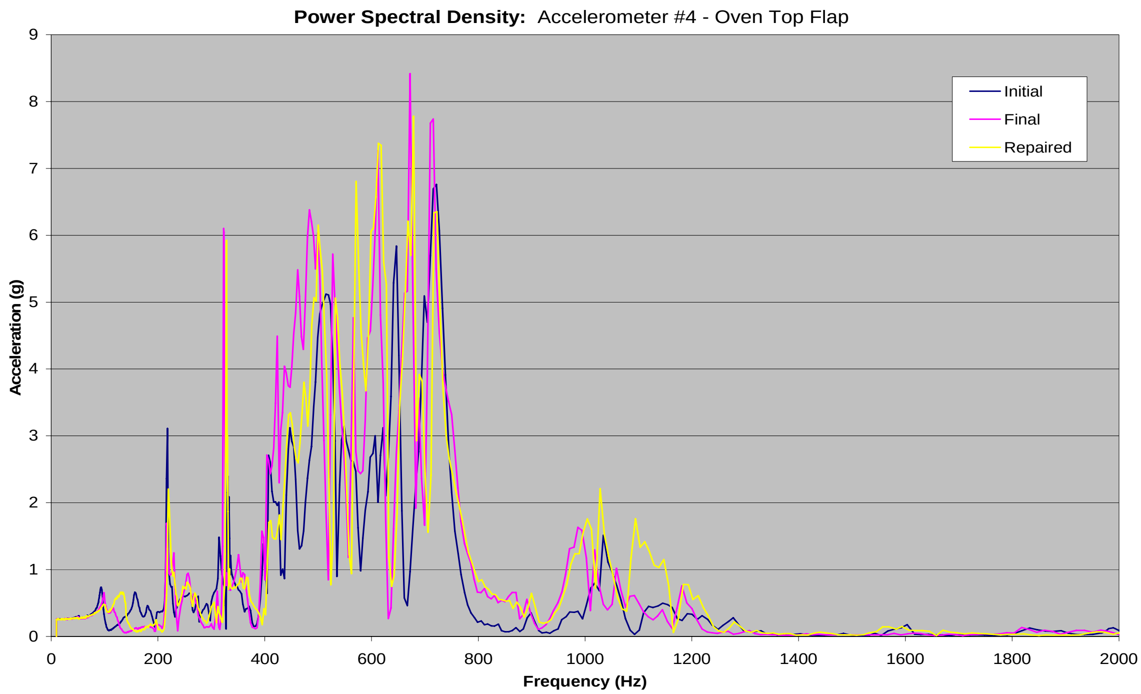


Figure D.23 Z Axis Random Vibration Accelerometer #4 PSDs

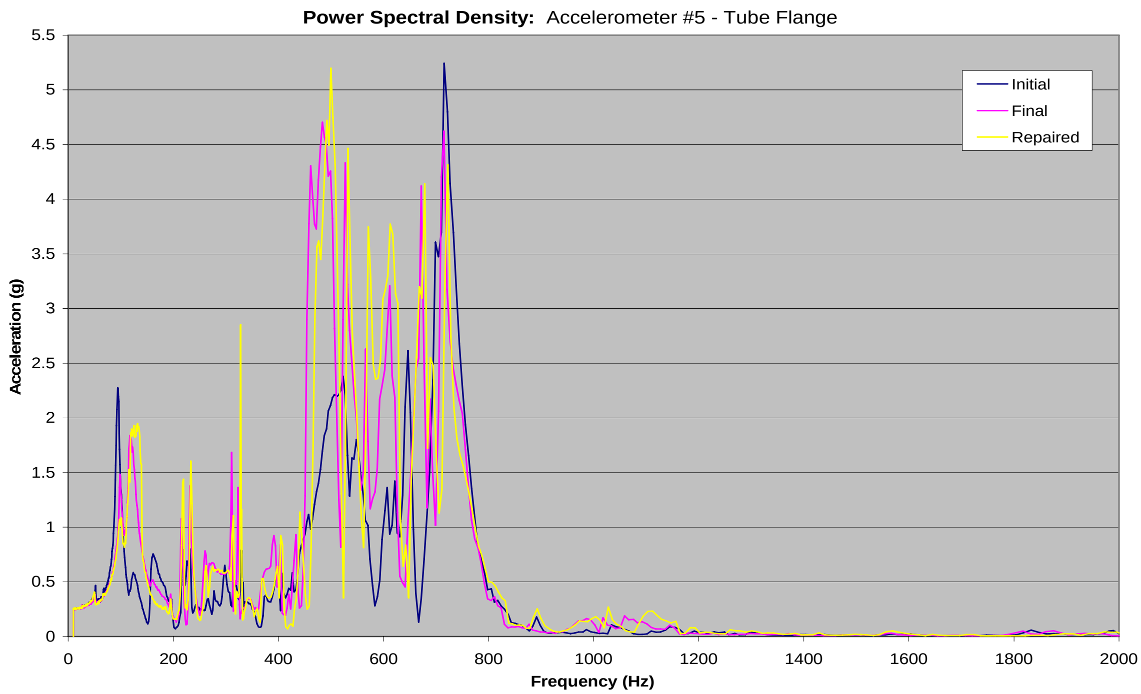


Figure D.24 Z Axis Random Vibration Accelerometer #5 PSDs

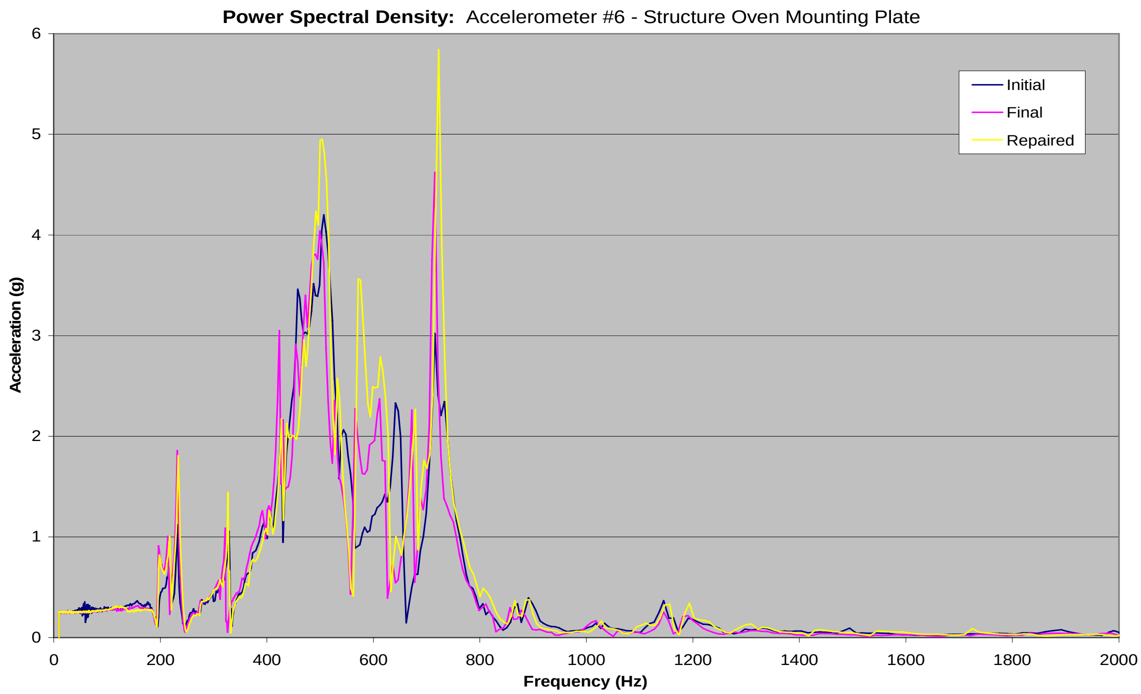


Figure D.25 Z Axis Random Vibration Accelerometer #6 PSDs

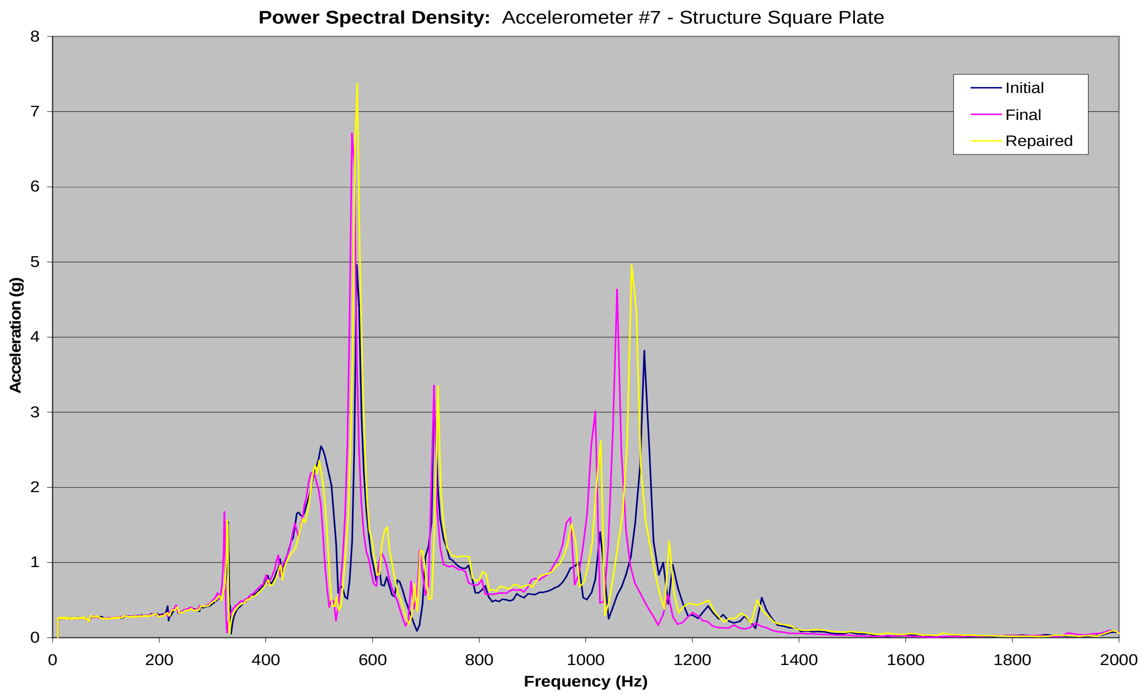


Figure D.26 Z Axis Random Vibration Accelerometer #7 PSDs

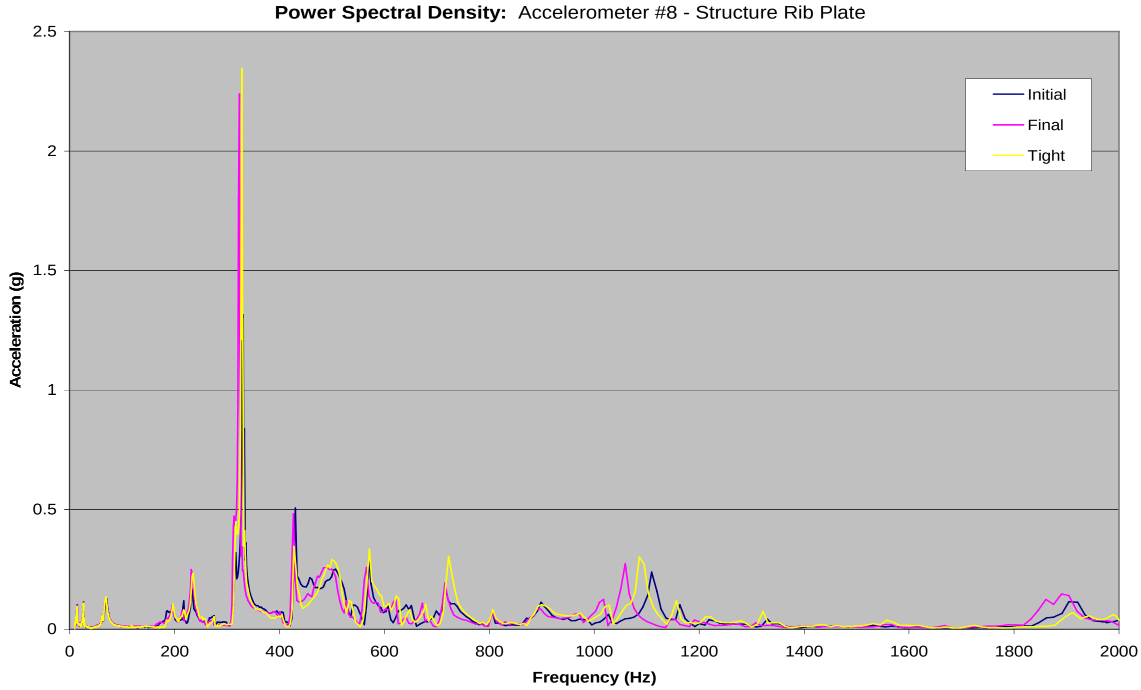


Figure D.27 Z Axis Random Vibration Accelerometer #8 PSDs

Appendix E: RIGEX FEM Results

Four final RIGEX FEM models were analyzed using NX Nastran for FEMAP software. The four combinations were massed without shroud, massed with shroud, un-massed without shroud, and un-massed with shroud. For ease of comparison, the results from the massed models were placed next to each other in Section E.1 and the results of the un-massed models are side-by-side in Section E.2. The natural frequency and mode shape data for the first five modes of each model are shown. Each figure includes a color scale to indicate the relative Von Mises stress distribution throughout the structure. The stress and displacement values shown are of little importance in eigenvalue analysis because they are arbitrarily scaled in FEMAP for visual clarity. However, the mode shape and location were maximum stresses appear gives insight as to where the structure will be most harshly burdened during launch environment loading.

E.1 Massed Model Results

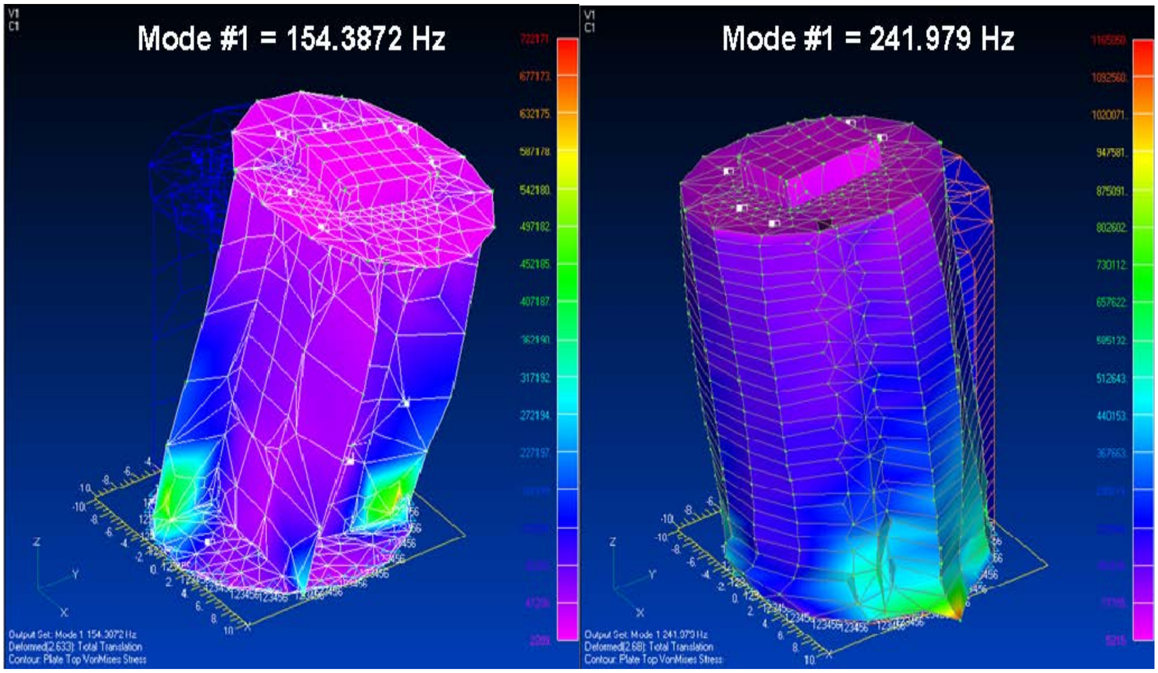


Figure E.1 Mode #1, Massed RIGEX FEM With and Without Shroud

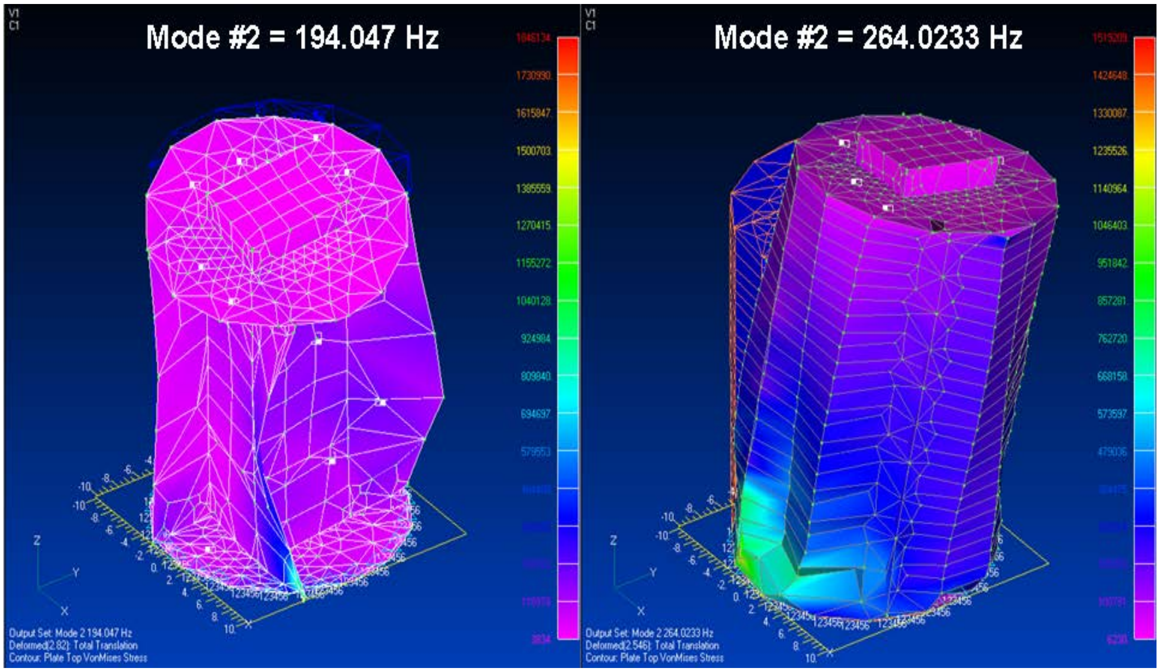


Figure E.2 Mode #2, Massed RIGEX FEM With and Without Shroud

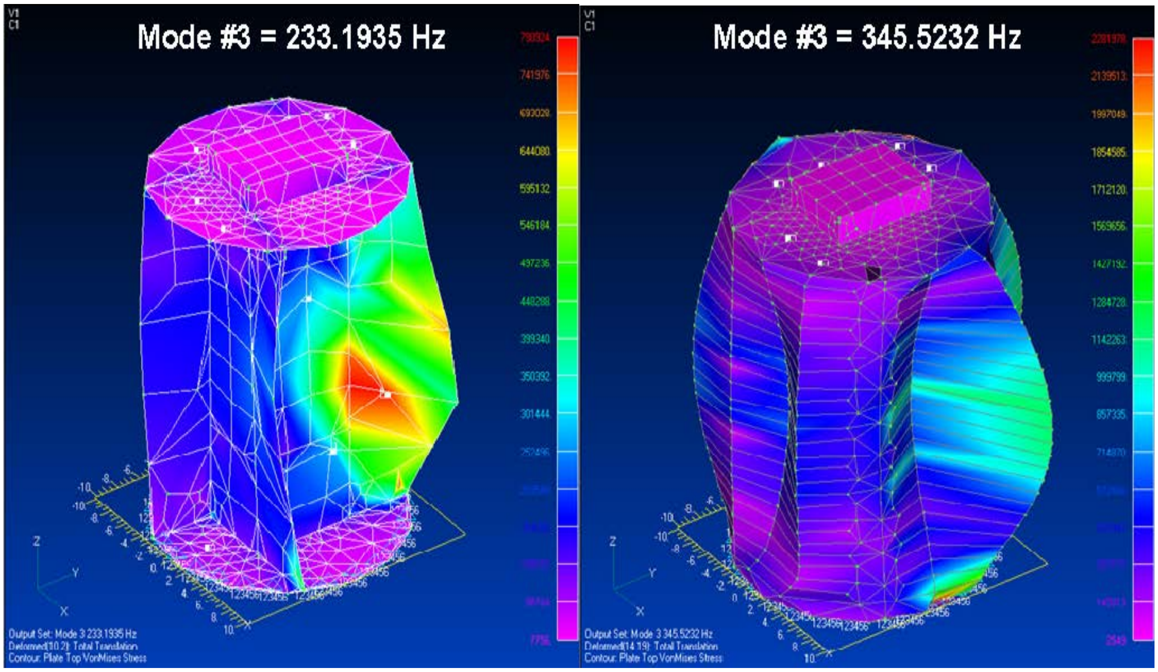


Figure E.3 Mode #3, Massed RIGEX FEM With and Without Shroud

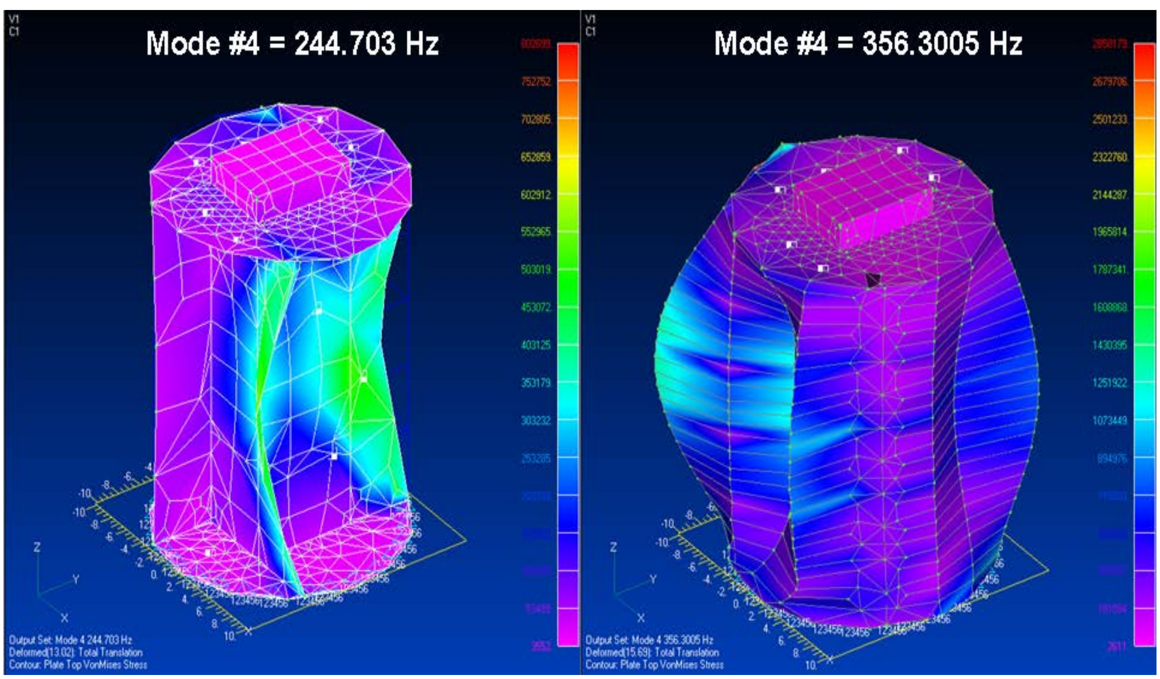


Figure E.4 Mode #4, Massed RIGEX FEM With and Without Shroud

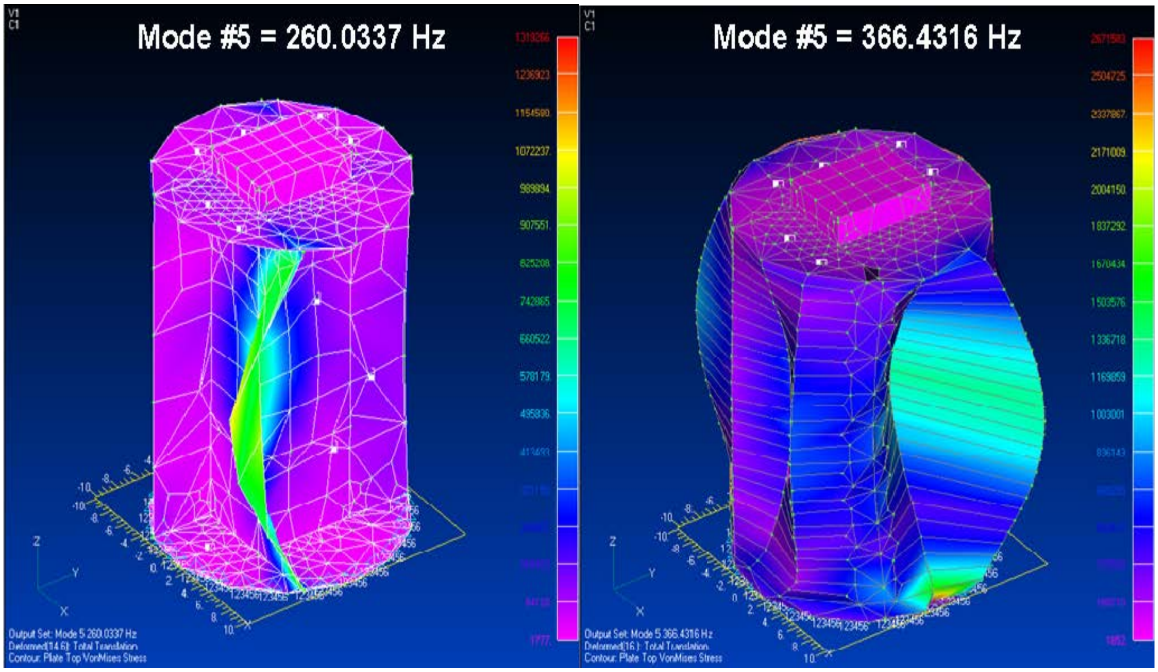


Figure E.5   Mode #5, Massed RIGEX FEM With and Without Shroud

E.2   Un-Massed Model Results

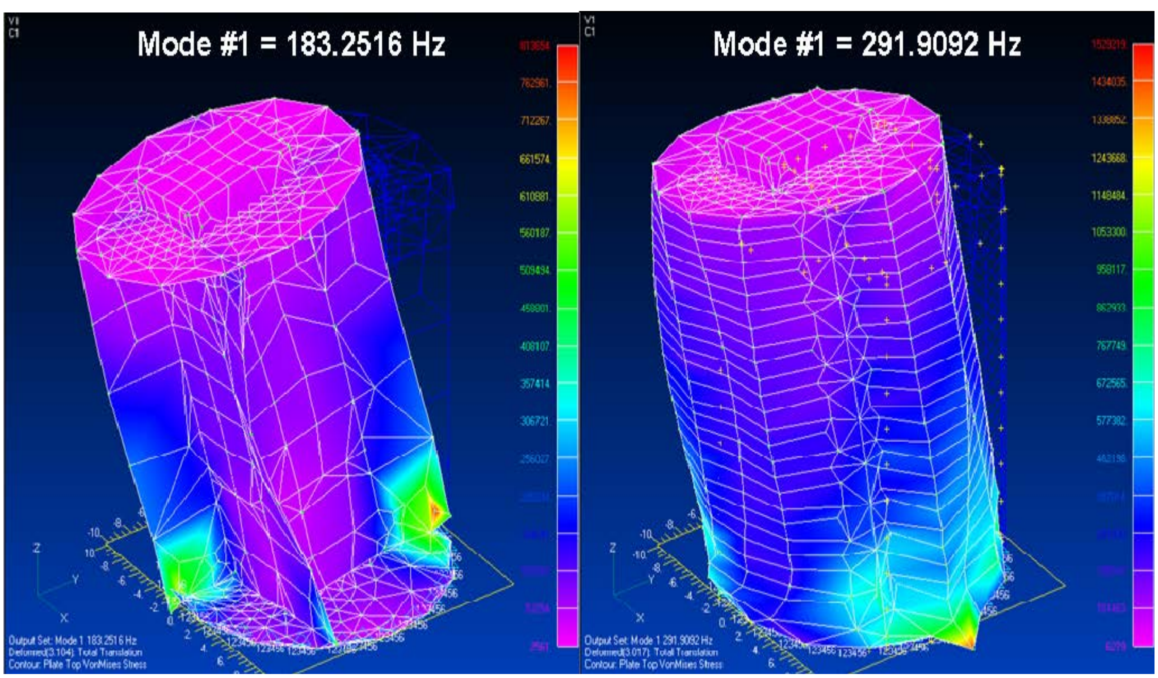


Figure E.6   Mode #1, Un-Massed RIGEX FEM With and Without Shroud

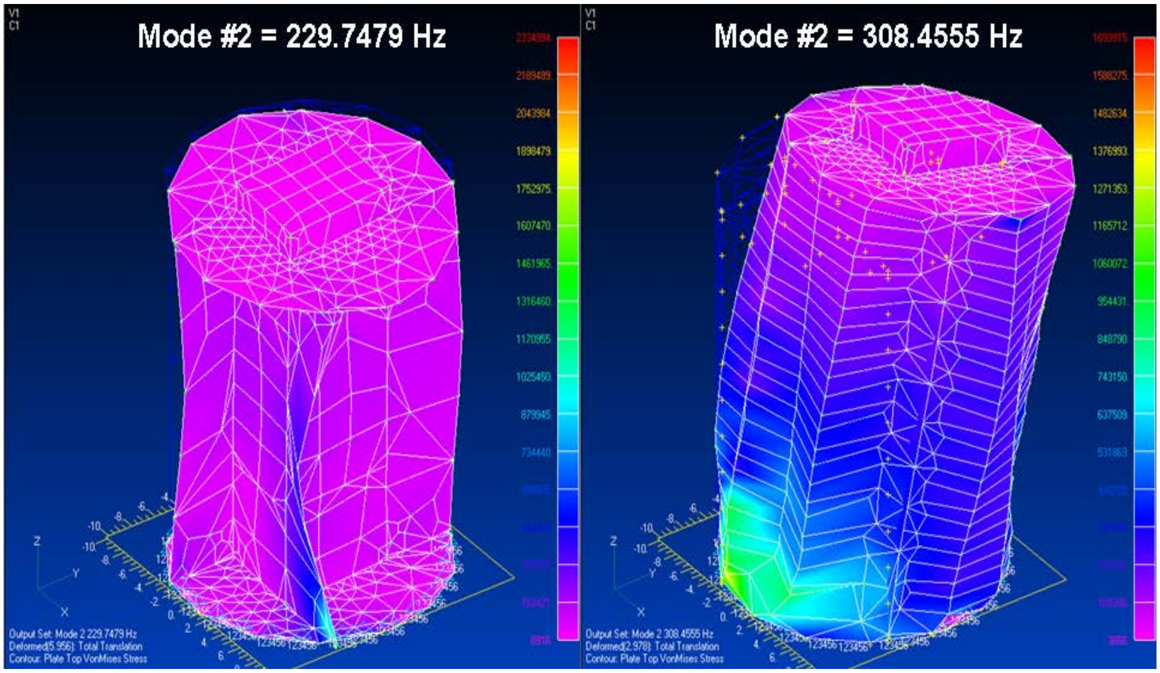


Figure E.7 Mode #2, Un-Massed RIGEX FEM With and Without Shroud

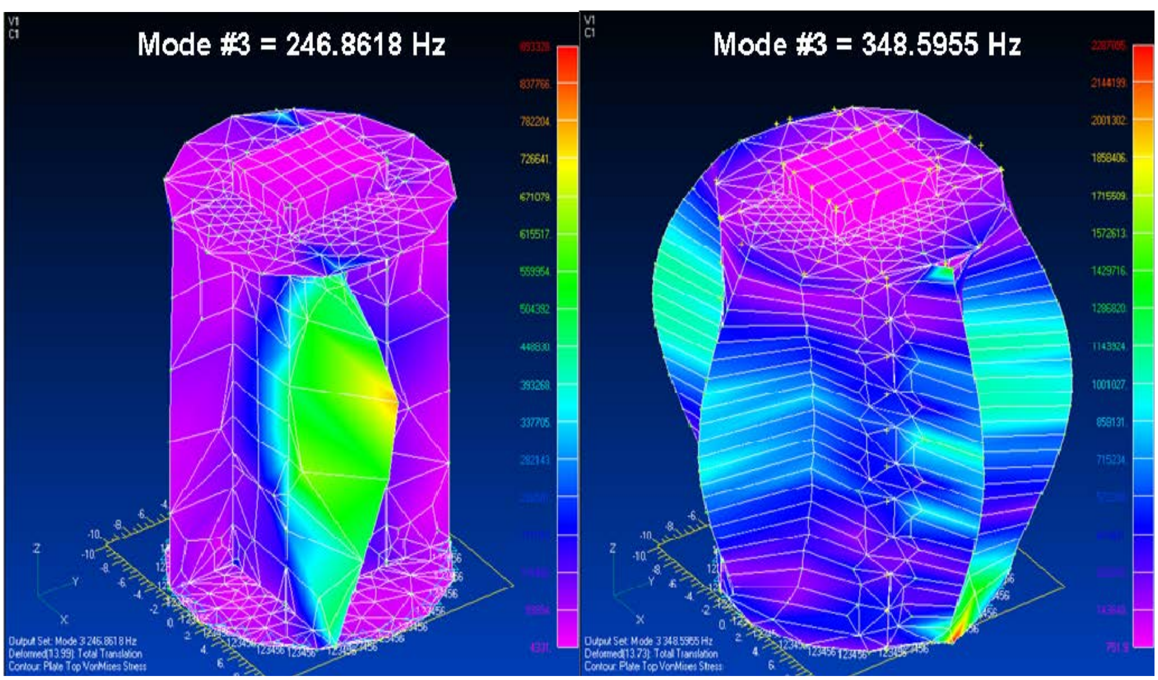


Figure E.8 Mode #3, Un-Massed RIGEX FEM With and Without Shroud

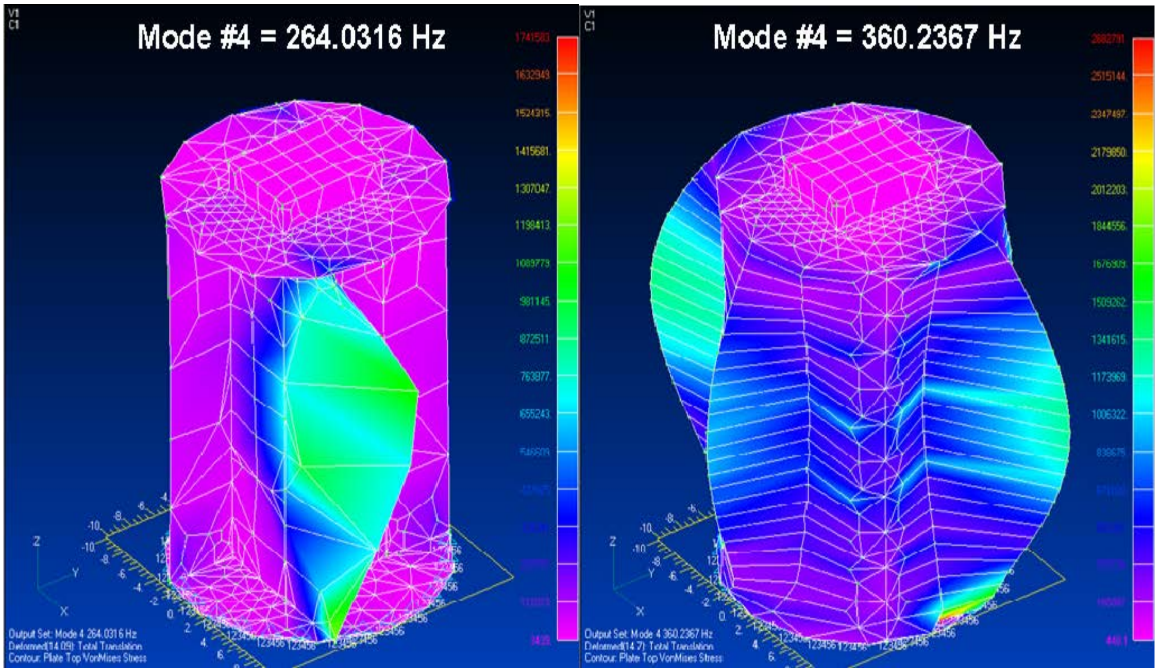


Figure E.9 Mode #4, Un-Massed RIGEX FEM With and Without Shroud

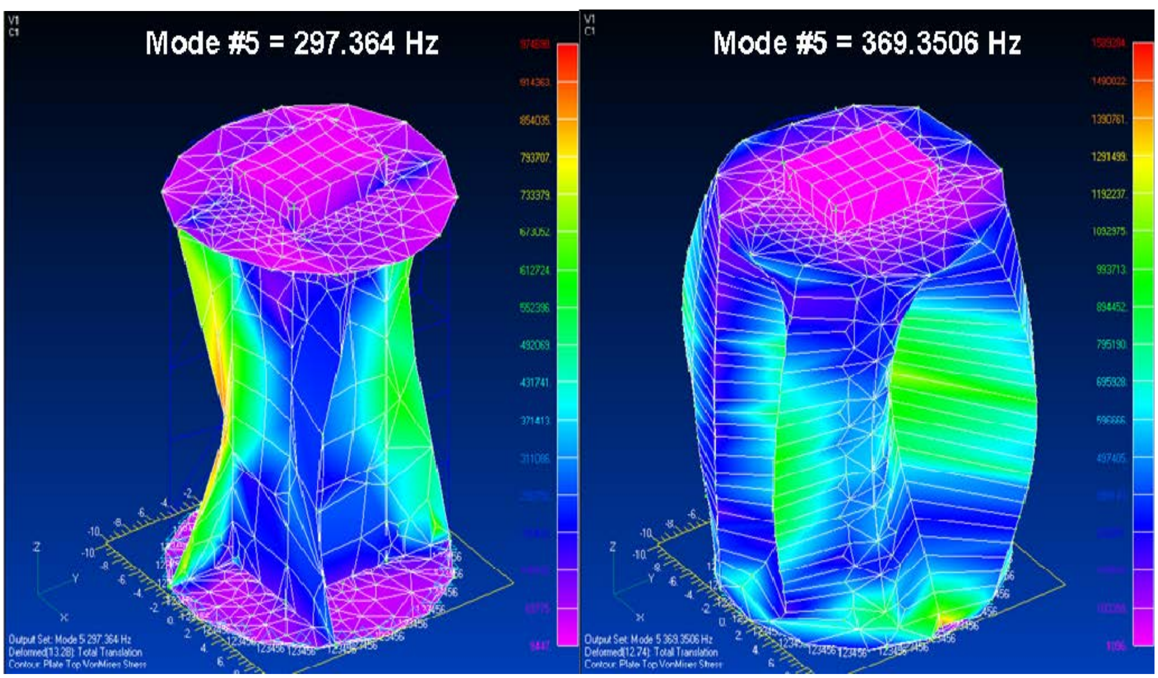


Figure E.10 Mode #5, Un-Massed RIGEX FEM With and Without Shroud

Bibliography

1. Belvin, Keith W. "Advances in Structures for Large Space Systems." AIAA 2004-5898. American Institute of Aeronautics and Astronautics, Inc. Space 2004 Conference and Exhibit. San Diego, California, 28-30 September 2004.

2. Boeing North American, Inc. Reusable Space Systems. *Space Flight Operations Contract: Shuttle Orbiter/Small Payload Accommodation Interfaces.* NSTS-21000-IDD-SML. Revision C. United Space Alliance, 19 February 1998.

3. Budde, Matthew J. Chief, DoD Shuttle/ISS Payload Integration and Operations, DoD Space Test Program, Johnson Space Center, Houston, Texas. Electronic Correspondence. 22 January 2006.

4. Cadogan, David P., and Stephen E. Scarborough. "Rigidizable Materials for use in Gossamer Space Inflatable Structures." AIAA 2001-1417. AIAA Gossamer Spacecraft Forum. 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. Seattle, Washington, 16-19 April 2001.

5. Cassapakis, Costa, and Mitch Thomas. "Inflatable Structures Technology Development Overview." AIAA 95-3738. American Institute of Aeronautics and Astronautics, Inc. 1995.

6. *Container for All Payload Ejections (CAPE) Hardware Users Guide (CHUG).* DoD Shuttle/ISS Payload Support Contract. Muniz Engineering, Inc. Johnson Space Center, Houston, Texas, 10 March 2003.

7. Cook, Robert D., David S. Malkus, Michael E. Plesha, and Robert J. Witt. *Concepts and Applications of Finite Element Analysis* (Fourth Edition). New York: John Wiley & Sons, Inc., 2002.

8. Derbes, Billy. "Case Studies in Inflatable Rigidizable Structural Concepts for Space Power." AIAA 99-1089. American Institute of Aeronautics and Astronautics, Inc. 1999.

9. DiSebastian III, John Daniel. *RIGEX: Preliminary Design of a Rigidized Inflatable Get-Away-Special Experiment.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, March 2001.

10. DoD Space Test Program Website. http://www.smc.kirtland.af.mil/stp/index.html. January 2006.

11. *FEMAP v9.0 User's Guide.* UGS Corporation. Plano, Texas, 2004.

12. FEMCI - Finite Element Modeling Continuous Improvement Website. http://femci.gsfc.nasa.gov/. NASA Goddard Space Flight Center. Greenbelt, Maryland, January 2006.

13. Freeland, R. E., G. D. Bilyeu, G. R. Veal, and M. M. Mikulas. "Inflatable Deployable Space Structures Technology Summary." http://www.lgarde.com/people/papers/iaf-98-I501.pdf.

14. Goodwin, Jeremy. *Detailed Design of the Rigidizable Inflatable Get-Away-Special Experiment.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, March 2006.

15. Guidanean, Koorosh, and David Lichodziejewski. "An Inflatable Rigidizable Truss Structure Based on New Sub-Tg Polyurethane Composites." AIAA 02-1593. American Institute of Aeronautics and Astronautics, Inc. 2002.

16. Holstein III, Raymond G. *Structural Design and Analysis of a Rigidizable Space Shuttle Experiment.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, March 2004.

17. Huang, John, Houfei Fang, Richard Lovick, and Michael Lou. "The Development of Large Flat Inflatable Antenna for Deep-Space Communications." AIAA 2004-6112. American Institute of Aeronautics and Astronautics, Inc. Space 2004 Conference and Exhibit. San Diego, California, 28-30 September 2004.

18. Jackson and Tull, Chartered Engineers. *Space Test Program (STP) Experimenters' Guide.* Space Test Program Office, Space and Missile Test and Evaluation Directorate, Space and Missile Systems Center, Air Force Material Command. Version 4.1. May 2004.

19. Johnson, ReAnn C. *RIGEX Kick Off TIM.* Teleconference Briefing Presented to RIGEX Team. DoD Human Spaceflight Payloads. 21 July 2005.

20. Kessler, Seth S., S. Mark Spearing, Mauro J. Atalla, Carlos E.S. Cesnik, and Constantinos Soutis. "Structural Health Monitoring in Composite Materials Using Frequency Response Methods."

21. L'Garde Incorporated Website. http://www.lgarde.com/index.html. January 2006.

22. Lichodziejewski, David, Gordon Veal, and Billy Derbes. "Spiral Wrapped Aluminum Laminate Rigidization Technology." AIAA 2002-1701. American Institute of Aeronautics and Astronautics, Inc. 2002.

23. Lindemuth, Steven N. *Characterization and Ground Test of an Inflatable Rigidizable Space Experiment.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, March 2004.

24. *Load Analyses of Spacecraft and Payloads.* NASA-STD-5002. NASA Technical Standard. National Aeronautics and Space Administration. Marshall Space Flight Center, Alabama, 21 June 1996.

25. *MB Dynamics Model C40HP Vibration Exciter User's Manual.* MB Dynamics. Cleveland, Ohio, March 1993.

26. *Military Handbook - MIL-HDBK-5H: Metallic Materials and Elements for Aerospace Vehicle Structures (Knovel Interactive Edition).* U.S. Department of Defense. http://www.knovel.com/knovel2/Toc.jsp?BookID=754&VerticalID=0.

27. Moeller, Chad R. *Design and Ground-Testing of an Inflatable-Rigidizable Structure Experiment in Preparation for Space Flight.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, June 2005.

28. Moody, David C. *Microporcessor-Based Systems Control for the Rigidized Inflatable Get-Away-Special Experiment.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, March 2004.

29. NASA Image Exchange. http://library.gsfc.nasa.gov/public/images.htm. The Goddard Space Flight Center Library. Greenbelt, Maryland, January 2006.

30. Nicholas, A.C., S.E. Thonnard, I. Galysh, P. Kalmanson, and B. Bruninga. "An Overview of the ANDE Risk Reduction Flight." AAS 05-401. American Astronautical Society. 2005.

31. *Payload Safety Review and Data Submittal Requirements.* NSTS/ISS 13830. Revision C. National Aeronautics and Space Administration. Johnson Space Center, Houston, Texas, July 1998.

32. *Payload Verification Requirements, Space Shuttle Program.* NSTS 14046. Revision E. National Aeronautics and Space Administration. Johnson Space Center, Houston, Texas, March 2000.

33. *Payload Vibroacoustic Test Criteria.* NASA-STD-7001. NASA Technical Standard. National Aeronautics and Space Administration. 21 June 1996.

34. Philley, Thomas Lee Jr. *Development, Fabrication, and Ground Test of an Inflatable Structure Space-Flight Experiment.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, March 2003.

35. Ritterhouse, Scott. *Canister for All Payload Ejections/Internal Cargo Unit (ICU) Structural Verification Plan.* CAPE-SVP-0001. Revision D. DoD Shuttle/ISS Human Spaceflight Payloads. Johnson Space Center, Houston, Texas, 4 May 2005.

36. Ritterhouse, Scott. *RIGEX Kick Off TIM Payload Integration Overview.* Teleconference Briefing Presented to RIGEX Team. DoD Human Spaceflight Payloads. 21 July 2005.

37. *Safety Policy and Requirements for Payloads Using the Space Transportation System.* NSTS 1700.7B. National Aeronautics and Space Administration. Johnson Space Center, Houston, Texas, January 1989.

38. Single, Thomas G. *Experimental Vibration Analysis of Inflatable Beams for an AFIT Space Shuttle Experiment.* Master's Thesis. Air Force Institute of Technology. Wright-Patterson AFB, Ohio, March 2002.

39. *Structural Design and Test Factors of Safety for Spaceflight Hardware.* NASA-STD-5001. NASA Technical Standard. National Aeronautics and Space Administration. Marshall Space Flight Center, Alabama, 21 June 1996.

40. Swagelok Website. http://www.swagelok.com/products.htm. February 2006.

41. Taber Industries Website. http://www.taberindustries.com/transducer/index.htm. February 2006.

42. Thomas, Mitchell. "Inflatable Space Structures: Redefining Aerospace Design Concepts Keeps Costs from Ballooning." http://www.lgarde.com/people/papers/structures.pdf.

Vita

Second Lieutenant Sarah K. Helms graduated from Torrey Pines High School in San Diego, California. She entered undergraduate studies at the United States Air Force Academy in Colorado Springs, Colorado where she was a member of Cadet Squadrons Thirteen and Twenty. She graduated from this institution with a Bachelor of Science degree in Astronautical Engineering and was commissioned in June 2004.

In September 2004, she entered the Graduate School of Engineering and Management, Air Force Institute of Technology with academic sequences involving spacecraft structures and structural modeling. Upon graduation, she will be assigned to Hill Air Force Base in Ogden, Utah. At Hill she will work in the AFRL/ML Advanced Composites Office.

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14. ABSTRACT

Many recent space technology concepts require large space structures such as solar arrays and large aperture antennas; however, tight constraints on payload mass and volume often preclude their launch. Employing inflatable, rigidizable structures can reduce mass and volume while providing sufficient packing flexibility and structural stiffness. AFIT has developed RIGEX to flight-test this type of structure.

RIGEX will test the deployment and structural characteristics of three thermoplastic composite Sub-Tg tubes. Once launched on the Space Shuttle in 2007, the spaceflight results will be compared to lab data to validate on-orbit reliability and ground test methods.

This paper documents three main RIGEX development items: the Space Shuttle integration process, random vibration testing of the oven assembly, and development and application of the RIGEX structural model. The RIGEX launch integration process has been laid out and the first milestones, the RIGEX Preliminary Design Review and Phase 0/I Safety Review, were successfully completed in September 2005. Subsequently, random vibration testing of the prototype RIGEX oven assembly validated its structural integrity. Furthermore, a RIGEX structural model was developed using the finite element approach and NX Nastran for FEMAP software. The RIGEX FEM produced a first natural frequency of 242 Hz, meeting the NASA requirement with a margin of over 140 Hz. Overall, the RIGEX structural design has rapidly matured, meeting all NASA requirements thus far.

15. SUBJECT TERMS

Space Technology, Inflatable Structures, Inflatable Rigidizable Structures, Rigidizable Inflatable Get-Away-Special Experiment, RIGEX, Structural Analysis, Finite Element Analysis, Modal Analysis, Random Vibration, Structural Response, Dynamic Response

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